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Risø-R-1200(EN)

Failure Database and Tools for Wind Turbine Availability and Reliability Analyses

The Application of Reliability Data for Selected Wind Turbines

Igor Kozine, Palle Christensen and Martin Winther-Jensen

Risø National Laboratory, Roskilde
January 2000

Abstract The objective of this project was to develop and establish a database for collecting reliability and reliability-related data, for assessing the reliability of wind turbine components and subsystems and wind turbines as a whole, as well as for assessing wind turbine availability while ranking the contributions at both the component and system levels. The project resulted in a software package combining a failure database with programs for predicting WTB availability and the reliability of all the components and systems, especially the safety system. The report consists of a description of the theoretical foundation of the reliability and availability analyses and of sections devoted to the development of the WTB reliability models as well as a description of the features of the database and software developed. The project comprises analysis of WTBs NM 600/44, 600/48, 750/44 and 750/48, all of which have similar safety systems.

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1 Introduction

Although Danish wind turbines (WTBs) are manufactured to very high standards, a permanent need exists for manufacturers to maintain performance records for the turbines they sell. This is no different from the situation with other types of quality goods. Such performance records facilitate the undertaking of reliability analyses for the preparation of performance documentation for use by the manufacturers' research and development departments and potential new customers. Reliability analyses can also be used to predict the performance of new designs. In order to be able to predict the reliability of a system one needs a reliability model and information about component fault frequencies. Failure data are usually available in most companies in the form of repair reports. Reliability modelling is a well-known tool in other areas and was introduced in the wind turbine industry by the EFP project "Safety Systems for Wind Turbines: Method for Evaluation of Failure Modes and Reliability" initiated in 1994. This project focussed on WTB Safety Systems, i.e. the systems preventing the turbine from going into over-speed under accidental circumstances.

A need remained, though, to extend these reliability considerations to the whole wind turbine with the additional aim of predicting its availability, i.e. its ability to produce electricity when wind speeds are adequate. The need to embrace the whole wind turbine – including the safety system – by a comprehensive reliability and availability analysis has necessitated revision and reconstruction of the database and software developed within the framework of the EFP project.

The present project comprises analysis of WTBs NM 600/44, 600/48, 750/44 and 750/48, all of which have similar safety systems. As these types of WTB differ from those analysed in the EFP project, it was necessary to revise the previously developed reliability models and establish new ones.

The project resulted in a software package combining a failure database with programs for predicting WTB availability and the reliability of all the components and systems, especially the safety system. The report consists of a description of the theoretical foundation of the reliability and availability analyses and of sections devoted to the development of the WTB reliability models as well as a description of the features of the database and software developed. Those who are not interested in the mathematical details and who focus on the analysis of the results can skip the theoretical part and proceed with the understanding of how to use the database.

The project was carried out by Risø National Laboratory in collaboration with NEG-MICON A/S. Funding was provided by the Danish Energy Agency (Project No. 51171/97-0021).

2 Objectives

The objective of this project was to develop and establish a database for collecting reliability and reliability-related data, for assessing the reliability of WTB components and subsystems and WTBs as a whole, as well as for assessing WTB availability while ranking the contributions at both the component and system levels.

The reliability analysis supposes development of the necessary reliability models, i.e. event trees and fault trees. All the calculations need to be embedded into a software package which together with the database is self-sufficient in performing all the analyses laid down in the methodology of the software system.

Different levels of access and security features need to be provided to exclude non-authorized access to the data and the calculation results.

3 Theoretical Foundation

3.1 Definitions

The most widely accepted definition of reliability is the ability of an item (product, system, etc.) to operate under designated operating conditions for a designated period of time or number of cycles [1]. This ability can be designated in terms of probability, with reliability being defined as follows [2]: Reliability is the probability that a product or a system will perform its intended functions satisfactorily (i.e. without failure and within specified performance limits) at a certain time, for a specified length of time, operating under specified environmental and usage conditions.

Availability analysis is performed to verify that an item has a satisfactory probability of remaining operational so that it can achieve its intended objectives. An item's availability can be considered as a combination of its reliability and maintainability. When no maintenance or repair is performed, reliability can be considered as instantaneous availability [1]. The following two definitions can be employed when defining availability [2]: Availability is the probability that a product or system will operate satisfactorily at any point in time, where the total time considered includes operating time, active repair time, administrative time and logistic time. An alternative definition [3] is that: Availability is the probability that a system will perform a specified function or mission under given conditions at a prescribed time.

Maintainability is the probability that a product or system will conform to specified conditions within a given period of time when maintenance action is performed according to prescribed procedures and resources.

3.2 Failure Analysis Approaches

Systems analysis approaches vary depending on the complexity of the system, the diversity of possible failure scenarios, and factors such as reparability/nonreparability, on-demand or permanent operation, etc. The following four approaches can be used for failure analysis of WTBs:

1. With systems regarded as simple with nonrepairable components, the manner in which they function is portrayed by connecting the units in a reliability block diagram [3]. All reliability block diagrams are classified as either series, parallel, k-out-of-n or cross-linked structures. These systems can be in one of two states: either operational or failed. To some extent such reliability diagrams can also be employed with repairable systems to assess the probability of failures between two down states and mean time between failures, as well as probabilities characterizing random time between two failures.
2. As system repair is generally initiated after a system has failed, a system is either operational or under repair. Hence, knowledge of system reliability is of less interest than knowledge of the system availability [3]. An availability analysis provides a characterization of system behaviour, enabling some features of maintainability to be modelled.
3. In multicomponent systems, one can rarely apply approaches 1 and 2, however, primarily because the number of components is too great and the interrelationships between the different subsystems are less trivial. Fault tree analysis is a method whereby a large number of events that interact to produce other events can be related using simple logical relationships (AND, OR, etc.), thereby enabling methodical construction of a structure representing the system.
4. Some systems can require a more comprehensive analysis with the involvement of different external conditions such as wind speed, lightning strikes, etc., in which case event tree analysis is the appropriate technique for assessing the probabilities of possible outcomes.

3.3 Assumptions for Reliability Modelling

All the systems of a WTB can be classified as either permanently working or working on demand. Permanently working systems encompass all systems except the safety system (SS). When undertaking reliability analysis it is convenient to allocate a third category: safety-related systems. Failure of safety-related systems affects not only the ability of the WTB to produce electricity but also the performance of the SS. The systems in question are the generator, the driveline and the gearbox. The failure of any of these systems causes loss of the possibility to bring the WTB to a safe halt. The reliability analysis of these three categories has specific features that are examined below.

The reliability and availability analyses are two different types of failure analysis, each reflecting a different facet of WTB performance. These two analyses are provided based on the data collected in the database.

The availability analysis takes into account all the failures that affect the WTB's ability to produce electricity due to the time spent on repairing the WTB. It does not allow for the frequency of failures. In general, when the average repair cost is a fraction of the initial equipment cost and the latter is high and the duration of down time affects the volume of production losses, one is interested in considering system repair. In such a system, time between failures, repair time and percentage of operating time in an interval are of more interest when analysing system performance. The availability function *A(t)* is defined as the probability that the system is operational at *time t*. In contrast, the reliability function *R(t)* is the probability that the system has operated *over the interval 0 to t*. If repair is not permitted, then *A(t)* reduces to system reliability *R(t)*. The reliability analysis thus takes into account the frequency of failure without considering the time spent for recovering the failed components.

In performing these analyses the following assumption is employed:

Failure of any component of a WTB (except the components constituting the safety system) leads to the WTB being shut down for repair of the component, during which time the WTB remains idle.

This assumption defines the structure of the reliability block diagram and the fault tree. All the components can thus be considered to be connected in series, i.e. the block diagram is a series structure and all the events in the fault tree are connected through OR gates (Figures 1 and 2). Thus the WTB fails if any of n components fail or if component 1 fails or component 2 fails and so on.

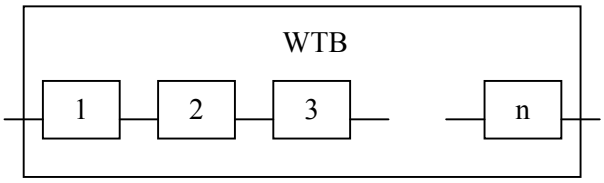


Figure 1. Reliability block diagram of a WTB, n is the number of components in the WTB

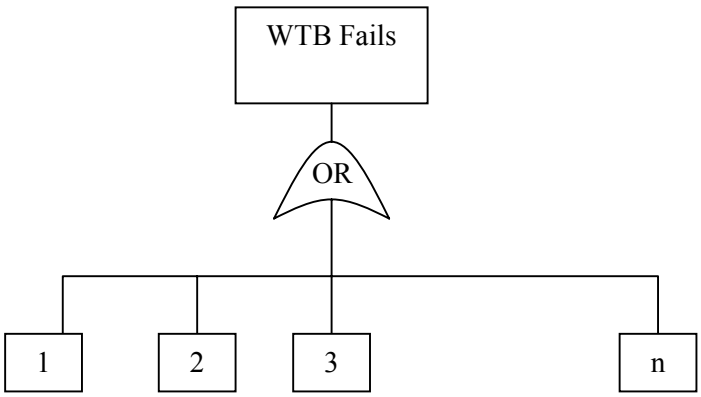


Figure 2. Fault tree for WTB failure

The SS failure analysis is twofold. Firstly, some SS failures affect WTB performance through extending the repair time. Such failures can be revealed (1) when the SS is activated on demand, or (2) during a periodic test control. If there is a failure in the SS and the WTB can be brought to a safe halt the repair time spent on recovering the SS simply decreases the availability of the WTB, thus contributing to the total unavailability. Such failures are taken into account in the availability analysis. Secondly, some SS failures might affect the WTB's ability to be maintained in a safe mode. Such failures are of particular interest and their likelihood must be analysed by means of reliability analysis conducted using event tree and fault tree analyses.

3.4 Availability Analysis of Permanently Working Components and Systems

Let T_{ij} represent the (random) length of the jth operating period having mean $\hat{T}_i$ for the ith component, and D_{ij} the (random) length of the jth replacement having mean $\hat{D}_i$ for the ith component, where j=1,2,…; i=1,2,…,n, and n is the number of components in the system under consideration. Figure 3 illustrates such an alternating sequence of operating and replacement periods.

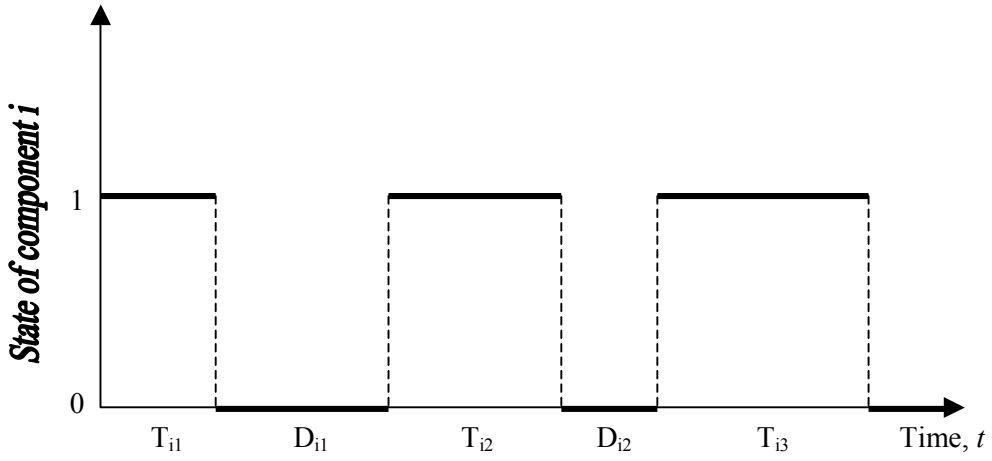


Figure 3. Alternating failure and repair for component i.

To assess WTB availability the model assumes the following:

(a) The system is in series and a system failure thus coincides with a component failure.
(b) During replacement of a failed component all other components remain in "suspended animation". When replacement of the failed component is completed, the remaining components abstract operation. At that instant they are not "as good as new", but only as good as they were when the system stopped operating.

As t becomes large, the availability function reaches the following steady-state value [2]:

$$\mathrm{A} = \left(1 + \sum_{i=1}^{n} \frac{\hat{D}_i}{\hat{T}_i}\right)^{-1} = \left(1 + \sum_{i=1}^{n} \frac{\lambda_i}{\mu_i}\right)^{-1} \tag{1}$$

where λ_i and μ_i are the mean failure rate and repair rate of the ith component, respectively.

It is known (see, for example [2]) – or can be inferred from (1) independently by inserting the assessments of $\hat{D}_i \approx \frac{1}{N_i}\sum_{j=1}^{N_i} D_{ij}$ and $\hat{T}_i \approx \frac{1}{N_i}\sum_{j=1}^{N_i} T_{ij}$, where N_i is the number of failures of the *i*th component during [0,T] – that the average availability of a system in [0,T] is the expected proportion of time the system is operating during [0,T], i.e.

$$\mathrm{A} = \frac{T^{op}}{T} \tag{2}$$

In the specific case of a WTB, we are also interested in the average availability, A, of WTBs of the same type, where A is defined as

$$A = \frac{1}{N^{WTB}} \sum_{i=1}^{N^{WTB}} A_i = \frac{1}{N^{WTB}} \frac{\sum_{i=1}^{N^{WTB}} T_i^{op}}{T} = \frac{1}{N^{WTB}} \frac{\sum_{i=1}^{N^{WTB}} T_i^{op}}{T} \tag{3}$$

where $\mathrm{N}^{\mathrm{WTB}}$ is the total number of WTBs of the same type and T_i^{op} is the total operation time of the ith WTB within the interval [0,T]. Equation (3) is only really valid if all $\mathrm{N}^{\mathrm{WTB}}$ are put into operation at the same time 0 and are in operation until the present time. In reality this is not the case, as the various starting dates are generally different and some of the WTBs can be put out of operation completely. Equation (3) thus has to be rewritten

$$A = \frac{1}{N^{WTB}} \sum_{i=1}^{N^{WTB}} \frac{T_i^{op}}{T_i} \tag{4}$$

where T_i is the total calendar time worked by the ith WTB. Equation (4) is used to assess the average availability of specific types of WTB. Knowledge of the availability of each type of WTB will enable identification of the most unreliable specific WTBs. Availabilities $\mathrm{A_i}$ are ranked in order of increasing $\mathrm{A_i}$ starting from the lowest $\mathrm{A_i}$. A specific WTB occupying the first place is the most unreliable as regards availability.

In order to identify the most unreliable subsystems and components it is useful to determine the unavailability *U* represented as

$$U = \frac{1}{N^{WTB}} \sum_{i=1}^{N^{WTB}} U_i = \frac{1}{N^{WTB}} \sum_{i=1}^{N^{WTB}} \frac{T_i^{down}}{T_i} = \frac{1}{N^{WTB}} \sum_{i=1}^{N^{WTB}} \frac{1}{T_i} \sum_{j=1}^{N^{Sys}} T_{ij}^{down} =$$

$$\frac{1}{N^{WTB}} \sum_{i=1}^{N^{WTB}} \frac{1}{T_i} \left(\sum_{j=1}^{N^{Sys}-1} T_{ij}^{down} + T_{ik}^{down} \right) = \frac{1}{N^{WTB}} \sum_{i=1}^{N^{WTB}} \frac{T_{ik}^{down}}{T_i} + \frac{1}{N^{WTB}} \sum_{i=1}^{N^{WTB}} \frac{1}{T_i} \sum_{j=1}^{N^{Sys}-1} T_{ij}^{down}, \quad (5)$$

where T_i^{down} is the total down time due to failures of the ith WTB within interval [0,T], N^{Sys} is the number of systems in a WTB of a certain type, T_{ij}^{down} is the total down time due to failures of the jth system in the ith WTB. The term $\frac{1}{N^{WTB}} \sum_{i=1}^{N^{WTB}} \frac{T_{ik}^{down}}{T_i}$ was extracted from the average unavailability to calculate the contribution to this reliability characteristic made by the kth system. Comparing two systems k and m, their contributions differ by the terms $\sum_{i=1}^{N^{WTB}} T_{ik}^{down}$ and $\sum_{i=1}^{N^{WTB}} T_{im}^{down}$. When ranking the systems' contribution to unavailability it is thus sufficient to rank the terms $\sum_{i=1}^{N^{WTB}} T_{ik}^{down}$. Ranking the systems according to the summary down time will portray the weakest systems with respect to their contribution to the unavailability.

Ranking by systems might be not informative enough to show what design improvements would have the greatest effect on WTB availability. Identifying the weakest components in a particular type of WTB can thus be very useful when trying to identify the most effective improvements. A measure of the contribution at a component level can be introduced using the following unavailability representation, which is similar to equation (5) should be done:

$$U = \frac{1}{N^{WTB}} \sum_{i=1}^{N^{WTB}} \frac{T_i^{down}}{T_i} = \frac{1}{N^{WTB}} \sum_{i=1}^{N^{WTB}} \frac{1}{T_i} \sum_{j=1}^{N^{Comp}} T_{ij}^{down} = \frac{1}{N^{WTB}} \sum_{i=1}^{N^{WTB}} \frac{T_{im}^{down}}{T_i} + \frac{1}{N^{WTB}} \sum_{i=1}^{N^{WTB}} \frac{1}{T_i} \sum_{j=1}^{N^{Comp}-1} T_{ij}^{down}, \quad (6)$$

where N^{Comp} is the number of components in a WTB and T_{ij}^{down} is the total down time due to failures of the jth system in ith WTB. Unlike (5) the term $\frac{1}{N^{WTB}} \sum_{i=1}^{N^{WTB}} \frac{T_{im}^{down}}{T_i}$ was extracted from the average unavailability in order to be able to calculate the contribution made to the unavailability by the mth component. As with the system contribution, it can be inferred that in order to rank the components according to their contribution to the unavailability it is sufficient to rank the terms $\sum_{i=1}^{N^{WTB}} T_{im}^{down}$.

Another useful ranking characteristic is that expressing the contribution to the unavailability made by the system components, namely:

$$\frac{1}{N^{WTB}} \sum_{i=1}^{N^{WTB}} \frac{T_{ik}^{down}}{T_i} = \frac{1}{N^{WTB}} \sum_{i=1}^{N^{WTB}} \frac{1}{T_i} \sum_{j=1}^{N_k^{Comp}} T_{ijk}^{down} = \frac{1}{N^{WTB}} \sum_{i=1}^{N^{WTB}} \frac{1}{T_i} \left(\sum_{j=1}^{N_k^{Comp}-1} T_{ijk}^{down} + T_{imk}^{down} \right) =$$

$$\frac{1}{N^{WTB}} \sum_{i=1}^{N^{WTB}} \frac{T_{imk}^{down}}{T_i} + \frac{1}{N^{WTB}} \sum_{i=1}^{N^{WTB}} \frac{1}{T_i} \sum_{j=1}^{N_k^{Comp}-1} T_{ijk}^{down}, \quad (7)$$

where N_k^{Comp} is the number of components in the kth specific system, T_{ijk}^{down} is the total down time caused by the jth component situated in the kth system in the ith WTB. Thus, the coefficient of relative component contribution to the unavailability of a system can be calculated as the component's contribution to the availability divided by the system contribution:

$$C_{mk}^{U} = \frac{\sum_{i=1}^{N^{WTB}} \frac{T_{imk}^{down}}{T_i}}{\sum_{i=1}^{N^{WTB}} \frac{T_{ik}^{down}}{T_i}} = \frac{\sum_{i=1}^{N^{WTB}} T_{imk}^{down}}{\sum_{i=1}^{N^{WTB}} T_{ik}^{down}} \tag{8}$$

3.5 Reliability Analysis of Permanently Working Components and Systems

Reliability assessments are measures of the frequency of failure, but without taking into account repair time. They characterize individual properties of components without relating to the performance of the system of which they are a part. A usual way of representing reliability is through the failure rates.

The general formula for assessing the failure rate of a component is:

$$\lambda = \frac{N}{N^{\Sigma} T} \tag{9}$$

where N is the number of failures of a component during interval [0,T], and N^{Σ} is the total number of components under observation. As regards WTBs, (9) can be rewritten

$$\lambda_i = \frac{\sum_{j=1}^{N^{WTB}} N_{ij}}{N^{WTB} M_i T^{\Sigma}} \tag{10}$$

where N_{ij} is the number of failures of the ith component of the jth WTB, M_i is the number of similar components in one WTB, and T^{Σ} is the total operational time worked by N^{WTB} WTBs of a given type.

The parameter T^{Σ} can be calculated in different ways depending on the nature of the available data. If failure data are collected for all wind turbines in operation from the point they entered service, then $T^{\Sigma} = \sum_{j=1}^{N^{WTB}} t_j$, where t_j is the total time of operation of the *j*th wind turbine of a given type. In our case, the failure data are collected from a fixed time in the past $\boldsymbol{t}_{Past}$, which supposes that some failures have not been reported and that these unreported periods of time have to be excluded. Moreover, different WTB life histories have to be taken into account when calculating the total operational time (see Fig. 4) expressed as

$$T^{\Sigma} = (t_{\mathrm{Pr}es} - t_{Past}) N^{WTB} - \sum_{i=1}^{N^{fWTB}} (t_{\mathrm{Pr}es} - t_i^f) - \sum_{i=1}^{N^{sWTB}} (t_i^s - t_{Past}) \tag{11}$$

where $\mathbf{t}_{\mathrm{Past}}$ is the date of the first failure reported in the database, N^{fWTB} is the number of wind turbines removed from operation within the interval [$\mathbf{t}_{\mathrm{Past}}$, $\mathbf{t}_{\mathrm{Pres}}$], N^{sWTB} is the number of wind turbines entered into service within the interval [$\mathbf{t}_{\mathrm{Past}}$, $\mathbf{t}_{\mathrm{Pres}}$]. The remaining variables are explained in Fig. 4.

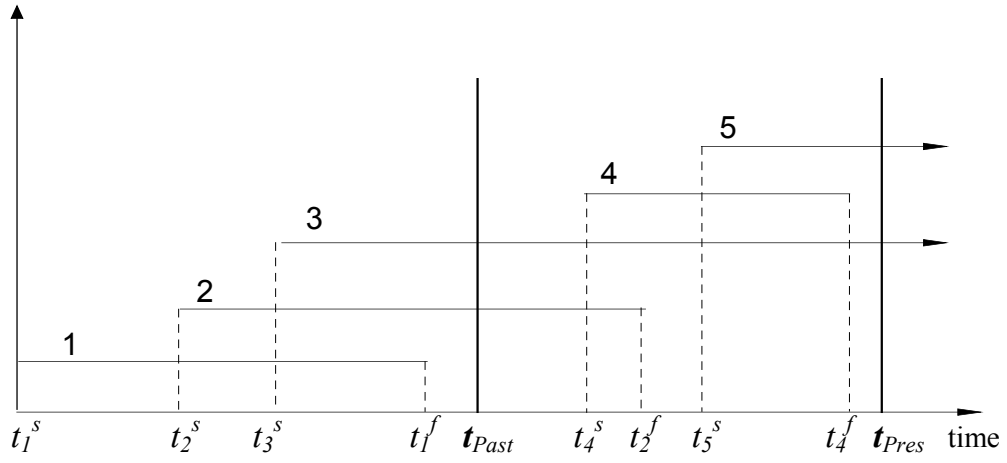


Figure 4. Possible wind turbine life history t_i^s – time of initiation of the ith wind turbine operation, t_i^f – the cessation of the ith operation, t_{Past} – the time data collection was initiated, t_{Pres} – present time

The reliability, $P_i(t)$, of the ith component at time t can be defined as follows:

$$P_i(t) = \exp(-\lambda_i t) \cong 1 - \lambda_i t$$

When all the components are connected in series, the reliability of the WTB is calculated by the expression

$$P(t) = \prod_i P_i(t) = \prod_i (1 - \lambda_i t) \tag{12}$$

There might be some practical difficulty associated with the use of equation (10) due to the fact that some of the component failures might not occur within the analysed time interval and because equation (10) thus gives the failure rate as zero, i.e. the component is ideal from the reliability point of view. No component can ever be completely reliable, however, If no failures have been reported for a component, the lower reliability can be estimated on the basis of the conservative assumption that a failure might possibly take place within the next small time interval, i.e. $N_{ij} = 1$. Since the upper limit is not known for this case one can hypothetically (optimistically) assume that $N_{ij} = 0$.

The lower and upper reliabilities can consequently be determined using equation (12) by employing optimistic and pessimistic assumptions.

3.6 Reliability Analysis of Components and Systems Working on Demand

Subsystems and components constituting the SS are not operational all the time but need to be activated when there is a demand to halt the rotor or to maintain it in a safe mode. The probability that they will work on demand, ϖ_i, is expressed as

$$\varpi_i = \frac{\lambda_i}{\Lambda^{Dem}}$$

where λ_i is the failure rate of the ith subsystem or component, Λ^{Dem} is the average number of demands per year. λ_i is determined using equation (10).

In the present case, the number of demands per year is defined as:

$$N^{Dem} = \lambda^{Grid\ \text{loss}} + \lambda^{Generator} + \lambda^{Drive\ \text{line}} + \lambda^{Gearbox} + \lambda^{ws>25},$$

where $\lambda^{Grid\ \text{loss}}$, $\lambda^{Generator}$, $\lambda^{Drive\ \text{line}}$, and $\lambda^{Gearbox}$ are determined using equation (10), and $\lambda^{Grid\ \text{loss}}$ and $\lambda^{ws>25}$ are the average rates of grid loss and wind speed exceeding 25 m/s, respectively, determined from external sources.

4 Reliability Analysis of the Safety System

4.1 Basic Concepts of Event Tree Analysis

Event trees are inductive logic methods for identifying the various possible outcomes of a given initiating event. The initiating event of an event tree is either a system failure or an external event that can end in an undesired outcome. The effect of an initiating event on a system depends on what might happen next and the sequence of occurrences. As a result, several possible scenarios can be developed that could possibly have severe impact on the system and the environment.

From a theoretical point of view the probability that a specific system will fail is conditional on the initiating events. To analyse a SS, which is activated on demand, we have first to identify all possible initiating events. The probability of its failure can then be calculated as

$$P(\overline{SS}) = \sum_i P(\overline{SS} / I_i) P(I_i)$$

where $\overline{SS}$ designates the failure of the SS and I_i is the ith initiating event. All the initiating events I_i together constitute the partitioning of the set of all possible initiating events. This means that $\sum_i P(I_i) = 1$, i.e. all possible initiating events are included in the analysis. Sometimes it is unrealistic to consider all the events and instead only those making the greatest contribution to the final probability are taken into account. This is usual practice when analysing the reliability and risk of large-scale technical systems such as chemical plants or nuclear power plants.

Initiating events can be considered under different external conditions (in our case – different wind speeds). In this case, we have to calculate the resultant probability conditional on all possible combinations of the initiating events and the conditions I_iC_j. The final equation for calculating the probability that the SS will fail is thus

$$P(\overline{SS}) = \sum_j \sum_i P(\overline{SS} / I_i C_j) P(I_i C_j) = \sum_j \sum_i P(\overline{SS} / I_i C_j) P(I_i) P(C_j) \qquad (13)$$

4.2 Assumptions for the Safety System

The mission of the SS is different from the rest of a WTB in that it is activated on demand in order to bring the WTB to a safe condition, i.e. one in which the rotor is either completely halted or is rotating at a permissible rotation speed. SS reliability can thus be defined as:

The reliability of a WTB safety system is the probability that the safety system is able to bring the WTB to a safe condition on demand under given conditions for a specified time interval.

As pointed out above, a characteristic of WTBs is that some of the components and systems are permanently operational and at the same time affect the performance of the SS. The components in question are the generator, the gearbox, and the driveline connecting the gearbox and the generator. When the demand arises to stop a WTB the generator connected to the electrical grid acts as an additional SS

subsystem and the reliability of the SS thus depends on the reliability of the SS. A failure of the gearbox affects the reliability of the SS such that rotation of the rotor cannot be halted by the grid connected to the generator and the mechanical brake cannot be engaged. Failure of the driveline disrupts the "grid–generator" connection, thereby increasing the probability of SS failure.

Six groups of demands activating the SS can be identified: 1) a component failure in the WTB, 2) grid loss, 3) generator failure, 4) driveline failure, 5) gearbox failure, and 6) wind speed exceeding 25 m/sec. These events are assumed to be mutually exclusive, i.e. any two of them cannot happen simultaneously. This further implies that while the WTB is being brought to a stop state, the other initiating events (demands) cannot take place. This simplification is necessary to simplify the reliability models and is practically justifiable.

Different weather conditions (wind speed) can require different functionality of the SS, and must therefore be taken into account when working out scenarios for possible SS failures. The following five wind speed ranges are chosen for the reliability analysis: 1) ws<5 m/s, 2) 5 m/s≤ws<10 m/s, 3) 10 m/s≤ws<20 m/s, 4) 20 m/s≤ws<25 m/s, and 5) ws≥25 m/s. The lowest range, ws<5 m/s, is of no interest in the present context since a WTB cannot experience over-speed under such conditions. The highest range, ws≥25 m/s, is regarded as an initiating event. The following six different scenarios will thus be analysed:

Initiating event	Wind speed	Designation
Component failure, $\mathbf{I_1}$	5 m/s≤ws<10 m/s, $\mathbf{C_1}$	$\mathbf{I_1C_1}$
	10 m/s≤ws<20 m/s, $\mathbf{C_2}$	$\mathbf{I_1C_2}$
	20 m/s≤ws<25 m/s, $\mathbf{C_3}$	$\mathbf{I_1C_3}$
Grid loss, $\mathbf{I_2}$	5 m/s≤ws<10 m/s, $\mathbf{C_1}$	$\mathbf{I_2C_1}$
	10 m/s≤ws<20 m/s, $\mathbf{C_2}$	$\mathbf{I_2C_2}$
	20 m/s≤ws<25 m/s, $\mathbf{C_3}$	$\mathbf{I_2C_3}$
Generator failure, $\mathbf{I_3}$	5 m/s≤ws<10 m/s, $\mathbf{C_1}$	$\mathbf{I_3C_1}$
	10 m/s≤ws<20 m/s, $\mathbf{C_2}$	$\mathbf{I_3C_2}$
	20 m/s≤ws<25 m/s, $\mathbf{C_3}$	$\mathbf{I_3C_3}$
Drive-line failure, $\mathbf{I_4}$	5 m/s≤ws<10 m/s, $\mathbf{C_1}$	$\mathbf{I_4C_1}$
	10 m/s≤ws<20 m/s, $\mathbf{C_2}$	$\mathbf{I_4C_2}$
	20 m/s≤ws<25 m/s, $\mathbf{C_3}$	$\mathbf{I_4C_3}$
Gearbox failure, $\mathbf{I_5}$	5 m/s≤ws<10 m/s, $\mathbf{C_1}$	$\mathbf{I_5C_1}$
	10 m/s≤ws<20 m/s, $\mathbf{C_2}$	$\mathbf{I_5C_2}$
	20 m/s≤ws<25 m/s, $\mathbf{C_3}$	$\mathbf{I_5C_3}$
ws≥25 m/s, $\mathbf{I_6}$		$\mathbf{I_6}$

4.3 Event Tree Construction

In working out the event trees we were concerned with identifying the sequences ending in SS failure states. Sequences that end in success states were therefore generally omitted. Since we are analysing 6 systems that might affect SS reliability, each of which can have two states (success and failure), the total number of states is 2^6=64. As only a few are failure states there is no need to depict them all. On the event trees shown in Appendix I, sequences ending in failure states are shown by bold lines with the logical function representation written above them. In this context, "AB" denotes that "the sequence takes place if system A is in a success state **and** system B is in a success state" while "$A\overline{B}$"

denotes that "the sequence takes place if system A is in a success state **and** system B is in a failure state". On the event trees, the systems involved are denoted as follows:

A	B	C	D	E	F
Magnetic valve	**Pop-out valve system**	**1 tip brake deploys**	**2 tip brakes deploy**	**3 tip brakes deploy**	**Mechanical brake**

It should be noted that the event trees for the initiating events "Grid loss", "Generator failure" and "Driveline failure" will be identical because the occurrence of any of these events means that the WTB cannot be maintained in a safe mode by the "grid–generator" connection.

In conclusion, it is only necessary to develop seven event trees to model the (un)reliability of the SS.

Initiating event "Component failure"

This initiating event implies that when there is a demand to stop a WTB due to a component failure in the WTB, both the generator and the grid are operational. Thus under all wind speeds (except ws≥25 m/s, which will be considered separately) the WTB will be kept safe by the generator connected to the electrical grid. Hence under these circumstances an undesired outcome will not occur and all the three conditional probabilities $P(\overline{SS} / I_i C_j)$ will be equal to zero.

Initiating event "Grid loss"/"Generator failure"/"Driveline failure" and wind speed "5 m/s≤ws<10 m/s"

To ensure WTB safety under these conditions it must be possible for either one tip brake to deploy or the mechanical brake to deploy.

The event tree depicting all possible failure scenarios for initiating event "Grid loss" and condition "5 m/s≤ws<10 m/s" is shown in Appendix I, Fig. 1. It can be seen that there are 5 different ways to reach a failure state. The summarizing logical formula for failure of the SS is thus

$$\overline{SS}/\mathrm{I_2C_1} = AB\overline{C}\,\overline{F} \text{ OR } A\overline{B}\,\overline{C}\,\overline{F} \text{ OR } \overline{A}B\overline{C}\,\overline{F} \text{ OR } \overline{A}\,\overline{B}F \text{ OR } \overline{A}\,\overline{B}\,\overline{C}F$$

which can be simplified as

$$\overline{SS}/\mathrm{I_2C_1} = \overline{C}\,\overline{F}\,(AB \text{ OR } A\overline{B} \text{ OR } \overline{A}B \text{ OR } \overline{A}\,\overline{B}) \text{ OR } \overline{A}B\overline{F}$$

Furthermore, the expression in parentheses is a certain event that takes place with a probability of 1 and hence can be omitted. The final canonical expression for failure of the SS is thus

$$\overline{SS}/\mathrm{I_2C_1} = \overline{F}(\overline{A}\,\overline{B} \text{ OR } \overline{C}) \qquad (14)$$

i.e. *"the SS fails if the mechanical brake fails **and** the magnetic valve fails **and** the pop-out system fails, **or** one tip brake cannot deploy".*

Initiating event "Grid loss"/"Generator failure"/"Driveline failure" and wind speed "10 m/s≤ws<20 m/s"

To ensure WTB safety under these conditions it must be possible for either one tip brake to deploy and the mechanical brake to deploy or for two tip brakes to deploy.

The event tree depicting all possible failure scenarios for the initiating event "Grid loss" and wind speed "10 m/s≤ws<20 m/s" is shown in Appendix I, Fig. 2. It can be seen that there are 6 different ways to reach a failure state. The summarizing logical formula for failure of the SS failure is thus

$$\overline{SS}/I_2C_2 = ABC\overline{D}\,\overline{F} \text{ OR } AB\overline{C} \text{ OR } A\overline{B}C\overline{D}\,\overline{F} \text{ OR } A\overline{B}\,\overline{C} \text{ OR } \overline{A}B\overline{D}\,\overline{F} \text{ OR } \overline{A}\,\overline{B}$$

with the corresponding final canonical expression being

$$\overline{SS}/I_2C_2 = \overline{AB} \text{ OR } \overline{C} \text{ OR } \overline{D}\,\overline{F} \tag{15}$$

i.e. *"the SS fails if the magnetic valve fails **and** the pop-out system fails, **or** one tip brake cannot deploy, **or** two tip brakes cannot deploy **and** the mechanical brake fails".*

Initiating event "Grid loss"/"Generator failure"/"Driveline failure" and wind speed "20 m/s≤ws<25 m/s"

To ensure WTB safety under these conditions it must be possible for either two tip brakes to deploy and the mechanical brake to deploy or for three tip brakes to deploy.

The event tree for this case is shown in Appendix I, Fig. 3. Under these conditions there are 7 possible undesired outcomes. The final canonical expression for failure of the SS is

$$\overline{SS}/I_2C_3 = \overline{AB} \text{ OR } \overline{D} \text{ OR } \overline{E}\,\overline{F} \tag{16}$$

i.e. *"the SS fails if the magnetic valve fails **and** the pop-out system fails, **or** two tip brakes cannot deploy **or** three tip brakes cannot deploy **and** the mechanical brake fails".*

Initiating event "Gearbox failure" and wind speed "5 m/s≤ws<10 m/s"

To ensure WTB safety under these conditions it is sufficient that one tip brake can deploy. The other subsystems of the SS are not available.

The event tree for this case is shown in Appendix I, Fig. 4. The final canonical expression for failure of the SS is

$$\overline{SS}/I_5C_1 = \overline{AB} \text{ OR } \overline{C} \tag{17}$$

i.e. *"the SS fails if the magnetic valve fails **and** the pop-out system fails, **or** one tip brake cannot deploy".*

Initiating event "Gearbox failure" and wind speed "10 m/s≤ws<20 m/s"

To ensure WTB safety under these conditions it must be possible for two tip brakes to deploy. The other subsystems of the SS are not available.

The event tree for this case is shown in Appendix I, Fig. 5. The final canonical expression for failure of the SS is

$$\overline{SS}/I_5C_2 = \overline{AB} \text{ OR } \overline{C} \text{ OR } \overline{D} \tag{18}$$

i.e. *"the SS fails if the magnetic valve fails **and** the pop-out system fails, **or** one tip brake cannot deploy **or** two tip brakes cannot deploy".*

Initiating event "Gearbox failure" and wind speed "20 m/s≤ws<25 m/s"

To ensure WTB safety under these conditions it must be possible for three tip brakes to deploy. The other subsystems of the SS are not available.

The event tree for this case is shown in Appendix I, Fig. 6. The final canonical expression for failure of the SS is

$$\overline{SS}\,/I_5C_3 = \overline{AB}\ \text{OR}\ \overline{C}\ \text{OR}\ \overline{D}\ \text{OR}\ \overline{E} \tag{19}$$

i.e. *"the SS fails if the magnetic valve fails **and** the pop-out system fails, **or** one tip brake cannot deploy, **or** two tip brakes cannot deploy, **or** three tips cannot deploy"*.

Initiating event "ws≥25 m/s"

To ensure WTB safety at wind speeds exceeding 25 m/s it must be possible for three tip brakes to deploy.

The event tree developed for this case is given in Appendix I, Fig. 7. The final canonical logical expression for the SS failure is

$$\overline{SS}\,/I_4 = \overline{AB}\ \text{OR}\ \overline{E} \tag{20}$$

i.e. "the SS fails if the magnetic valve fails **and** the pop-out system fails, **or** three tip brakes cannot deploy".

4.4 Aggregated Model for Calculating the Probability of SS Failure

The effect of any of three initiating events I_2 (Grid loss), I_3 (Generator failure), and I_4 (Coupling failure) is similar in the sense that the WTB loses one of the possibilities to be maintained in a safe mode by the connection "grid-generator". The probability of SS failure can thus be expressed as

$$P(\overline{SS}) = P(\overline{SS}\,/\,I_2\ \text{OR}\ I_3\ \text{OR}\ I_4) + P(\overline{SS}\,/\,I_5) + P(\overline{SS}\,/\,I_6) \tag{21}$$

Each term in (21) is calculated on the basis of equations 14–20 as follows

$$\begin{aligned} P(SS\,/\,I_2\ \text{OR}\ I_3\ \text{OR}\ I_4) &= [P(I_2) + P(I_3) + P(I_4)][P(C_1)P(\overline{ABF}\ \text{OR}\ \overline{CF}) + \\ &\quad P(C_2)P(\overline{AB}\ \text{OR}\ \overline{C}\ \text{OR}\ \overline{DF}) + P(C_3)P(\overline{AB}\ \text{OR}\ \overline{D}\ \text{OR}\ \overline{EF})] \\ P(\overline{SS}\,/\,I_5) &= P(I_5)[P(C_1)P(\overline{AB}\ \text{OR}\ \overline{C}) + P(C_2)P(\overline{AB}\ \text{OR}\ \overline{C}\ \text{OR}\ \overline{D}) + \\ &\quad P(C_3)P(\overline{AB}\ \text{OR}\ \overline{C}\ \text{OR}\ \overline{D}\ \text{OR}\ \overline{E})] \end{aligned}$$

$$P(SS\,/\,I_6) = P(I_6)P(\overline{AB}\ \text{OR}\ \overline{E})$$

In order to determine the final expression for calculating the probability that the SS will fail it is necessary to take into account the fact that the intersections of some of the events in the above expressions are not empty. The probabilities of those non-empty intersections must appear with a "minus" sign. Some of the intersecting events do not appear implicitly, i.e. $\overline{C} \cap \overline{D} = \overline{C}$ (two tip brakes cannot deploy if none can deploy) and $\overline{D} \cap \overline{E} = \overline{D}$ (all three tips cannot deploy if two cannot deploy either).

The above conditional probabilities can be written as

$$P(\overline{SS}/I_2 \text{ OR } I_3 \text{ OR } I_4) = [P(I_2)+P(I_3)+P(I_4)][P(C_1)(P(\overline{A})P(\overline{B})P(\overline{F}) + \mathrm{P}(\overline{\mathrm{C}})P(\overline{F}) - P(\overline{F})) + P(C_2)(P(\overline{A})\mathrm{P}(\overline{\mathrm{B}}) + \mathrm{P}(\overline{C}) + \mathrm{P}(\overline{D})P(\overline{F}) - \mathrm{P}(\overline{C})P(\overline{F})) + P(C_3)(P(\overline{A})\mathrm{P}(\overline{\mathrm{B}}) + \mathrm{P}(\overline{D}) + \mathrm{P}(\overline{E})P(\overline{F}) - \mathrm{P}(\overline{D})P(\overline{F}))]$$

$$P(\overline{SS}/I_5) = P(I_5)[P(C_1)(P(\overline{A})P(\overline{B}) + P(\overline{C})) + P(C_2)(P(\overline{A})P(\overline{B}) + P(\overline{D})) + P(C_3)(P(\overline{A})P(\overline{B}) + P(\overline{E}))]$$

$$P(\overline{SS}/I_6) = P(I_6)[P(\overline{A})P(\overline{B}) + P(\overline{E})]$$

The final expression for calculating the probability that the SS will fail is

$$P(\overline{SS}) = [P(I_2)+P(I_3)+P(I_4)][P(C_1)(P(\overline{A})P(\overline{B})P(\overline{F}) + \mathrm{P}(\overline{\mathrm{C}})P(\overline{F}) - P(\overline{F})) + P(C_2)(P(\overline{A})\mathrm{P}(\overline{\mathrm{B}}) + \mathrm{P}(\overline{C}) + \mathrm{P}(\overline{D})P(\overline{F}) - \mathrm{P}(\overline{C})P(\overline{F})) + P(C_3)(P(\overline{A})\mathrm{P}(\overline{\mathrm{B}}) + \mathrm{P}(\overline{D}) + \mathrm{P}(\overline{E})P(\overline{F}) - \mathrm{P}(\overline{D})P(\overline{F}))] + P(I_5)[P(C_1)(P(\overline{A})P(\overline{B}) + P(\overline{C})) + P(C_2)(P(\overline{A})P(\overline{B}) + P(\overline{D})) + P(C_3)(P(\overline{A})P(\overline{B}) + P(\overline{E}))] + P(I_6)[(P(\overline{A})P(\overline{B}) + P(\overline{E})] \quad (22)$$

Probabilities $P(\overline{C}), P(\overline{D}),$ and $P(\overline{E})$ have to be calculated differently from the rest of the probabilities and we have to employ the binomial distribution of probabilities.

$P(\overline{C})$ is the probability of an event where one tip brake cannot deploy. If we denote one tip brake failure by $\overline{T}$ and take into account that there are three tip brakes, then

$$P(\overline{C}) = P(\overline{T})^3$$

$\overline{D}$ is an event where two tip brakes cannot deploy. This event takes place if none of the tip brakes can deploy or any two out of the three tip brakes cannot deploy. Assuming binomial distribution,

$$P(\overline{D}) = P(\overline{T})^3 + 3P(\overline{T})^2(1-P(\overline{T}))$$

$\overline{E}$ is an event where all three tip brakes cannot deploy together. This event takes place if none of the tip brakes can deploy, or any two of the three tip brakes cannot deploy, or all three tip brakes cannot deploy simultaneously. Thus,

$$P(\overline{E}) = P(\overline{T})^3 + 3P(\overline{T})^2(1-P(\overline{T})) + 3P(\overline{T})(1-P(\overline{T}))^2$$

4.5 System Reliability Modelling

Some of the events in equation (22) are trivial and their probabilities can be defined directly from the data collected in the database, or, in the case of wind conditions, from external sources of information. These events or conditions do not need to be broken down and no failure models are required for them. The probability of the grid loss, $P(I_2)$, and probabilities $P(C_1)$, $P(C_2)$, and $P(C_3)$ thus cannot be determined from the data stored in the database, but only from other data, and hence have to be stored in the database in the form of constants that can be periodically updated when more precise data become available.

Generator failure, $P(I_3)$

The generator consists of the following components, the failure of each of which will cause generator failure:

Bolte
RPM sensor
Støddæmper
Kobling
Lejer
Temperatursensor
Terminaler
Kabler
Slanger
Pumpe
Vanddækning

From the reliability standpoint, all of the components are connected in series, i.e. the generator fails if the "bolte" fails or "RPM sensor" fails or the "støddæmper" fails, etc. The probability of generator failure is thus

$$P(\text{Generator failure }) = 1 - P(\text{bolte}) \times P(\text{RPM sensor}) \times P(\text{støddæmper}) \times \ldots, \quad (23)$$

where all the terms are the probabilities that the individual components are in non-failure state.

Gearbox failure, $P(I_5)$

The gearbox consists of the following components, the failure of each of which will cause generator failure:

Bolte
Støddæmper
Split bushing
Lejer, pakninger
Olie
Suspension
Temperatursensor
Oliekøler
Olievarmer
Overtryksventil
Slanger
Slæbering
Pumpe

The probability of gearbox failure is thus calculated using an equation similar to equation (23).

Mechanical brake failure, P($\overline{F}$)

The mechanical brake consists of the following components, the failure of each of which will cause generator failure:

Bolte
Bremseskiver
Bremseklodser
Filter
Hydraulikstation
Hydraulikslanger
Ikke-returnventil
Magnetventil
Motor
Microswitch
Olie
Overløbssventil
Trykswitch
Bremsescoop
Akkumulator

The probability of mechanical brake failure is thus calculated using an equation similar to equation (23).

Tip brake failure, P($\overline{T}$)

A tip brake consists of the following components, the failure of each of which will cause generator failure.

Bolte
Vinge tip guides
Vinge cylinder
Vinge tip spring
Vinge tip
Vinge root
Wire
Surface
Forkant/bagkant
Sensor
Lynbeskyttelse

Hydraulic system, $P(\overline{A})$ and $P(\overline{B})$

The deployment of the tip brakes is activated by the hydraulic system. To enable the tips brakes to deploy oil must flow through either the magnetic valve (Appendix II, Position 13) or the pop-out system (Appendix II, Positions 19 and 55). These are considered independent subsystems of the SS.

The magnetic valve is processed in the database as one component and valve failure is designated $\overline{A}$.

The pop-out system is processed in the database as a two-component system that is considered to be in a state of failure if the "Sikkerhedsventil pop-out" fails and the "Sprængblik" fails, i.e. the components are connected in parallel from the reliability standpoint. This system failure is designated by $\overline{B}$.

5 Conceptual Database Structure and Capabilities

Now that all the calculations necessary for the availability and reliability analyses have been defined and the event and fault trees developed, the database structure and capabilities can be defined.

The following options are provided by the database:

1. Availability analysis

Assessment of the average availability of a certain type of WTB and ranking of all specific WTBs within a certain type sample according to availability.

Assessment of the contribution made by system unavailability to the average unavailability of a certain type of WTB and ranking the systems according to their contribution to unavailability.

Assessment of the contribution made by component unavailability to the average unavailability of a certain type of WTB and ranking the components according to their contribution to unavailability.

Assessment of the contribution made by component unavailability to the unavailability of the system to which the component belongs and ranking of the components according to their contribution to system unavailability.

Assessment of interannual variation in availability.

2. Information services (data analysis)

Screening, convoluting and reporting information in accordance with user requirements at the

Component level,
System level, and
Whole WTB level

3. Reliability analysis

- Reliability assessments of all components and systems and the reporting of them
- Reliability analysis of the SS subsystems and the SS as a whole
- Reliability analysis of the safety-related systems

6 Logical Data Model

In order to meet the objectives and theoretical requirements, three basic tables (Tables 1-3) and several subsidiary tables were created (Appendix III). The basic tables comprise the actual database and contain the basic information needed to make a decision on WTB performance, especially availability and reliability. The main reason for dividing the database into a series of tables is to avoid the redundancy in the data. The links between tables are provided by Primary and Foreign keys.

The table fields contain the option codes in those cases where it has been possible to classify them but not full names and definitions. Thus for the fields "*System, Component, Failure causes, Detection methods, Responsibility, WTB modes"* (see Table 1), all the options can be foreseen in advance and classified. The codes for these fields are consequently short. The decoding tables for these fields are the subsidiary tables. Except for the decoding function, these serve as menu options under data entry.

Each type of WTB has its own set of three basic tables and separate entrance, i.e. a separate database.

Tables 2-3 were mainly created to provide for quantitative reliability calculations. The field "Date of start" thus contains numbers for t_i^s (2), "Date of finish" for t_i^f (2), and "Test interval" for assessing the (un)availability of periodically inspected components, "Number" for m_i (1). The number of wind turbines in question, N_{WTB}, is equal to the number of records in the WTB table.

Main Table Table 1

Foreign key Foreign key

1	2	3	4	5	6	7	8	9	10	11	12
Rec. no.	WTB ID	System	Com-ponent	Comp ID	Date	kWh	Work order	Who made	WTB mode	Repair time	Repair man
1											
j											

13	14	15	16	17
Failure cause	Detect. method	Respon-sibility	Repair action	Remark

WTB Table Table 2

Primary key

	1	2	3
	WTB ID	Date of start	Date of finish
record 1			
record k			

Component Table Table 3

Primary key

	1	2	3	4	5	6
	Component	Component name	System	Test interval	Number	Price
record 1						
record n						

7 Security Features

The database is secured and access to it requires a user account and a password. The security system encompasses both group accounts and user accounts. Each user account must belong to a group account. There are default user and group accounts and newly created user and group accounts. The following group accounts are relevant for the security of the current database:

Groups: Admins (default)
Users (default)
NotAdmin
Typists

The user accounts are as follows:

Users	Member of group
Admin (default)	Users (default)
Administrator	Admins Users (default)
Analyst	NotAdmin Users (default)
Typist1	Typists Users (default)

The permitted operations within each group account are as follows:

Group	Permitted operations
Not Admin	Tables:* Read Design Read Data Queries (all): Read Design Read Data Forms (all): Open/Run Reports (all): Open/Run Macros (all): Open/Run Modules (all): Open/Run Read Design
Typists	Tables (all): Read Design Read Data Insert Data Forms (Components, Form0, Form1, Main Table, WTB) Open/Run Macros (all): Open/Run Read Design

*Some tables have more permitted operations, which are created and deleted when running the reliability calculations. These tables are not the objects of the logical model.Only one table "WTB" can be changed by a "NotAdmin" group user. These extra permitted operations are necessary to enable insertion of the current data into the field "Date of Finish" and to enable calculation of the total working experience.

The "Admin" group is the default group. The "Administrator" group is not listed in the table of permitted operations since all operations are permitted, especially the assignment of new group and user accounts and the granting of permitted operations.

The security system is organized in such a way that information about groups, users, registration IDs and passwords is saved in the workgroup information file. This file must be used with the database in order to be able to gain access to it. The current valid workgroup information file is RELIAB.MDW. When it was created, the following information was incorporated:

Name: Wind Turbines
Organization: NEG MICON
Workgroup ID: Reliab.

For more about the workgroup information file and the security system see Appendix IV or Help in MS Access.

The current security settings are listed below. It is necessary to know them in order to be able to gain access and change them in the future.

Newly created groups and users:

Group: NotAdmin
Registration ID: 999999

Group: Typists
Registration ID: 111111

Administrator:
Reg. ID: Igor
Password: Kozine
Analyst:
Reg. ID: Palle
Password: 123456
Typist1:
Reg. ID: Lise
Password: 234567

It should be remembered that the passwords and security data are case-sensitive.

8 User Manual

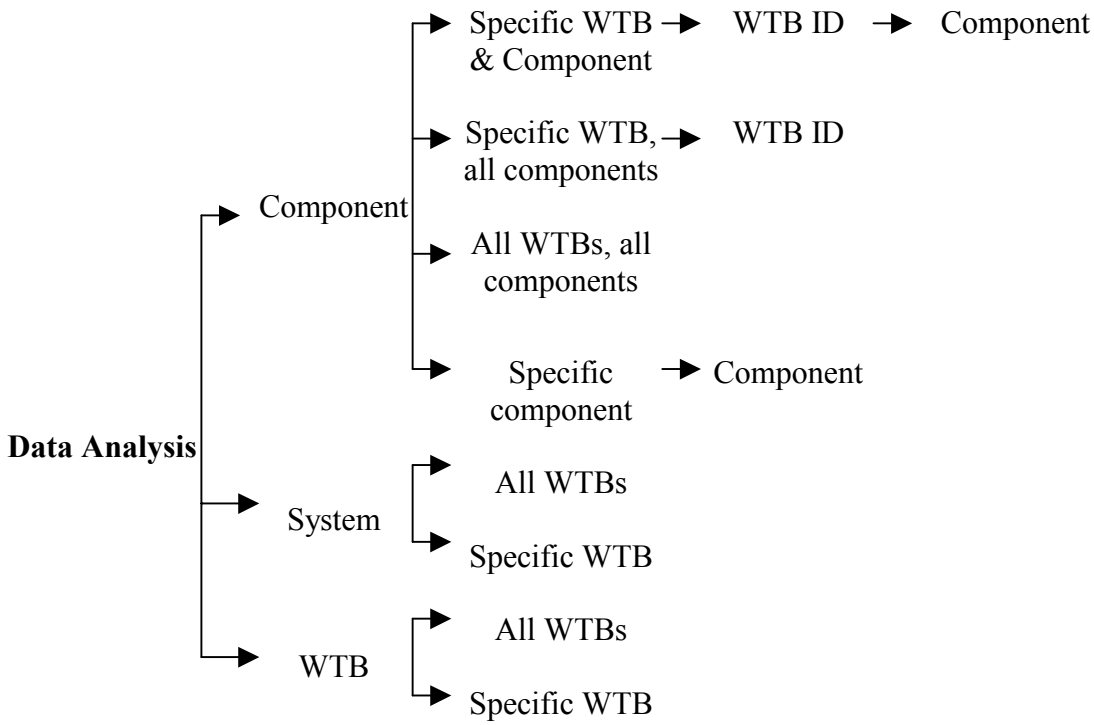
The database interface is self-contained in the sense that it is not necessary to use the Access toolbars but it is sufficient to use the command buttons on the forms created. The structure of the interface is uncomplicated and hence does not need to be described in detail. Some general notes on the options provided are given below.

The database is divided into two parts: Data Tables and Analyses.

"Data Tables" allows viewing, editing and data insertion in the tables "Main Table", "Components" and "WTB", the contents of which have been described above in Section 5 "Logical Data Model". These tables store all the information used in reliability analyses as well as some reliability-related data.

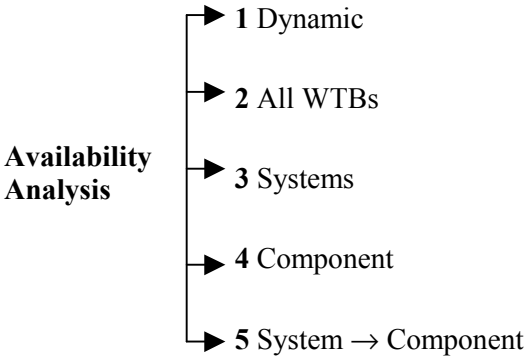
The option "Analyses" offers three suboptions: 1) Data Analysis, 2) Availability Analysis, and 3) Reliability Analysis.

The option structure of "Data Analysis" is as follows:



The result of any of the options is a report consisting of predefined data selected from the database. For example, the result of the option "Data Analysis – System – All WTBs" is a report such as shown on the following page. The other options represent similar reports depending on the request.

The option structure of "Availability Analysis" is as follows:

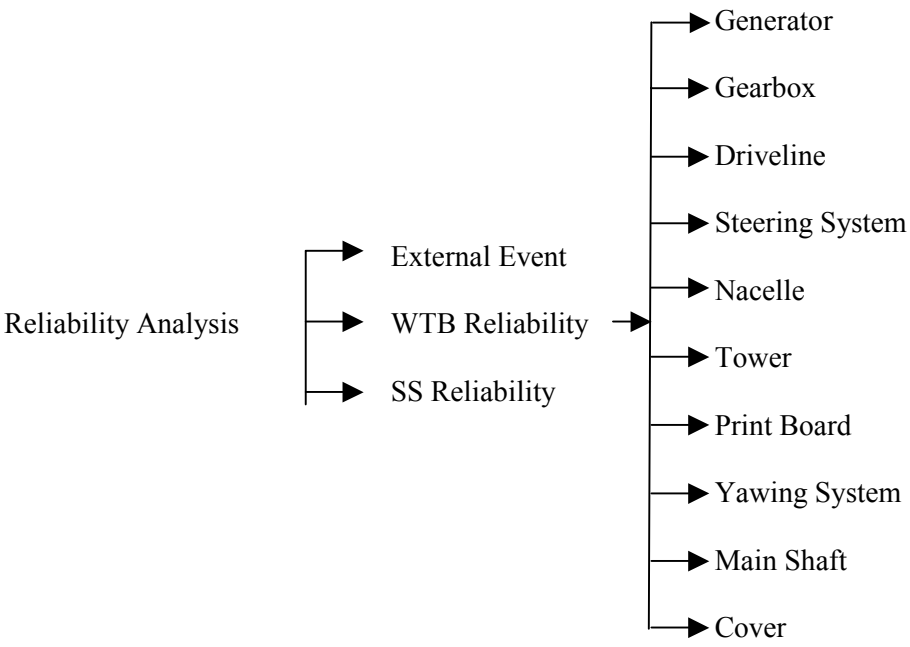


Option 1 "Dynamic" presents the average availability of the whole sample of WTBs by year, i.e. the option provides the possibility to see the interannual variation in availability.

Option 2 "All WTBs" provides a summarizing report of the average availability of the type of WTB in question and the unavailability of each WTB within the type. The WTBs are ordered by their unavailabilities starting with the most unreliable WTB.

Options 3, 4, and 5 provide the user with reports showing the contributions to the unavailability of 3) all the systems, 4) all the components reported in the database, and 5) all the components constituting a specified system.

The option structure of "Reliability Analysis" is as follows:



The option “External Event” does not perform any calculations and is an information option informing the user of the rates of the external events used in the SS reliability calculations. These rates can be subject to periodic correction if more precise data become available.

The option “WTB Reliability” calculates the reliability of any WTB system excluding the SS. Clicking any of the system name buttons will initialize the chain of the resulting reliability assessments of all the components constituting the system and the system as a whole.

The option “SS Reliability” calculates the reliability on demand for all the subsystems of the SS and the SS as a whole.

9 Notes for the System Developers

The relationships between the objects in the database are generally uncomplicated and the developer familiar with the basics of MS Access will easily be able to trace most of the actions performed. Nevertheless, there are some chains of related actions that can be difficult to fathom. The most complicated operations are those carried out for the reliability analyses. All the objects involved in these calculations are described below.

Option “Reliability Analysis → WTB Reliability → Generator” activates the following sequence of actions:

MS Access Object	Description
Macro: Macro Generator Reliability	*DeleteObject*: Table “Tab Gen Failure” *RunCode*: DateOfFinishEqualNow() *OpenQuery*: Query Gen Failure *RunCode*: Generator() *OpenReport*: Report Gen Failure *RunCode*: DateOfFinishOriginal()
Table: Tab Gen Failure	A subsidiary intermediate table deleted and recreated prior to each analysis.
Code: DateOfFinishEqualNow()	Inserts into the “WTB” table “Date of Finish” field the current date for those WTBs that are in operation at the time of the analysis. Action is needed for the calculation of the net working experience (years).
Make-Table Query: Query Gen Failure	Creates the table “Tab Gen Failure” based on the table “Components” and the select query “Query Gen Comp Failure”.
Query: Query Gen Comp Failure	Selects the generator component failures from the “Main Table”. Counts the number of failures for each of the components.
Code: Generator()	Based on the table “Tab Gen Failure” and the query “WTB Total Time”, this code calculates the reliabilities of all the generator components and the generator as a whole and transfers the results to the table “Tab Gen Failure”.
Query: WTB Total Time	Counts the number of WTBs under observation and listed in the table “WTB” and the net working experience accumulated by all the WTBs.
Report: Report Gen Failure	Reports all the calculated reliabilities and shows them on the screen. Is based on the table “Tab Gen Failure”
Code: DateOfFinishOriginal()	Restores the “WTB” table “Date of Finish” field to its original state. The current dates for those WTBs that are in operation at the time of the analysis.

The listed sequence of the actions is repeated each time the user makes a request and is similar for each of the following systems: Generator, Gearbox, Driveline, Steering system, Nacelle, Tower, Print board, Yawing system, Main shaft, and Cover. The differences lie in the names of some of the objects, which clearly indicate what system they are related to. In the case of the gearbox, for example, the names are “Macro Gearbox Reliability”, “Tab Gear failure”, “Query Gear Failure”, “Gearbox()”, and “Report Gear Failure”.

The reliability calculations for the Safety System and its subsystems are carried out differently.

MS Access Object	Description
Macro: Macro SS Rates	*RunMacro*: Macro Brake Reliability *RunMacro*: Macro Magnet Reliability *RunMacro*: Macro Pop-Out Reliability *RunMacro*: Macro Tips Reliability *RunMacro*: Macro Demand Rates *RunCode*: SSRates() *OpenReport*: Report SS Subsystems
Macro: Macro Brake Reliability	*DeleteObject*: Table "Tab Brake Failure" *RunCode*: DateOfFinishEqualNow() *OpenQuery*: Query Brake Failure *RunCode*: MechanicalBrake() *RunCode*: DateOfFinishOriginal()
Table: Tab Brake Failure	A subsidiary intermediate table deleted and recreated prior to each analysis.
Code: DateOfFinishEqualNow()	Inserts into the "WTB" table "Date of Finish" field the current date for those WTBs that are in operation at the time of the analysis. Action is needed for the calculation of the net working experience (years).
Make-Table Query: Query Brake Failure	Creates the table "Tab Brake Failure" based on the table "Components" and the select query "Query Brake Comp Failure".
Query: Query Brake Comp Failure	Selects the mechanical brake component failures from the "Main Table". Counts the number of failures for each of the components.
Code: MechanicalBrake()	Based on the table "Tab Brake Failure" and the query "WTB Total Time" the code calculates the failure rates of all the components of the mechanical brake and the system as a whole and transfers the results to the table "Tab Gen Failure". The results are intermediate and do not take into account the demand rates.
Code: DateOfFinishOriginal()	Restores the "WTB" table "Date of Finish" field to its original state. The current dates for those WTBs that are in operation at the time of the analysis are deleted.
The macros "Macro Magnet Reliability", "Macro Pop-Out Reliability", and "Macro Tips Reliability" are similar in structure to **"**Macro Brake Reliability", which is described above. The differences lie in the names of the objects, which are related to the names of the subsystems and are easily recognisable.	
Macro: Macro Demand Rates Since the failure of the generator, the gearbox, and the driveline are considered initiating events for activation of the SS, their failure rates are regarded as demand rates additional to the grid loss and wind speed >25 m/s. This macro activates all the actions needed to calculate the total demand rate.	*DeleteObject*: Table "Tab Drive Failure" *DeleteObject*: Table "Tab Gear Failure" *DeleteObject*: Table "Tab Gen Failure" *RunCode*: DateOfFinishEqualNow() *OpenQuery*: Query Drive Failure *OpenQuery*: Query Gear Failure *OpenQuery*: Query Gen Failure *RunCode*: DemandRate() *RunCode*: DateOfFinishOriginal()

Table: Tab Drive Failure	A subsidiary intermediate table deleted and recreated prior to each analysis.
Tables “Tab Gear Failure” and “Tab Gen Failure” have the same design as “Tab Drive Failure” and finally will keep the results of the calculations of their failure rates.	
Code: DateOfFinishEqualNow()	See above
Make-Table Query: Query Drive Failure	Creates the table “Tab Drive Failure” based on the table “Components” and the select query “Query Drive Comp Failure”.
Query: Query Drive Comp Failure	Selects the driveline component failures from the “Main Table”. Counts the number of failures for each of the components.
Queries “Query Gear Failure” and “Query Gen Failure” have the same design as “Query Drive Failure”.	
Code: DemandRate()	Based on the tables "Tab Gen Failure", "Tab Gear Failure", "Tab Drive Failure", and “External Events” and the query "WTB Total Time". Calculates the total demand rate and transfers the results to the table “Demand Rates”.
Code: DateOfFinishOriginal()	See above
Code: SSRates()	Based on the tables "Tab Brake Failure", "Tab Magnet Failure", "Tab Pop-Out Failure", "Tab Tips Failure", “External Events”, "SS Subsystem Reliab" and “Demand Rates”. Calculates the reliabilities of the SS subsystems and the SS as a whole on demand and transfers the results to the table "Tab SS Reliability".
Report: Report SS Subsystems	Reports the results of the SS reliability calculations based on the table "SS Subsystem Reliab".

All the objects in the database are interlinked and any changes in the design will lead to failure of some of the connected actions. Only the content of the Tables 1, 2, 3 and those shown in Appendix III and the table “External Events” can be changed. The table “External Events” can be periodically updated when more precise data become available. The contents of all the other tables cannot be changed.

An exception is the table “Components”. The components “Magnetventil”, “Sikkerhedsventil pop-out” and “Sprængblik” are referred to via their IDs in the queries “Query Magnet Comp Fail”, “Query Magnet Failure”, “Query Pop-Out Fail” and “Query Pop-Out Failure”. If due to some reason their ID numbers get changed, proper corrections must be done in the queries.

References

1. M. Modarres. What every engineer should know about reliability and risk analysis. Marcel Dekker, 1993.
2. L. Rademakers et al., Reliability Analysis Methods for Wind Turbines. Task 1 of the project: Probabilistic Safety Assessment for Wind Turbines.
3. N. J. McCormick. Reliability and Risk Analysis. Academic Press. 1981.

APPENDIX I

Event Trees for Wind Turbine Failure States

Figure 1. Event tree for initiating event "Grid loss" and condition "5 m/s≤ws<10 m/s"

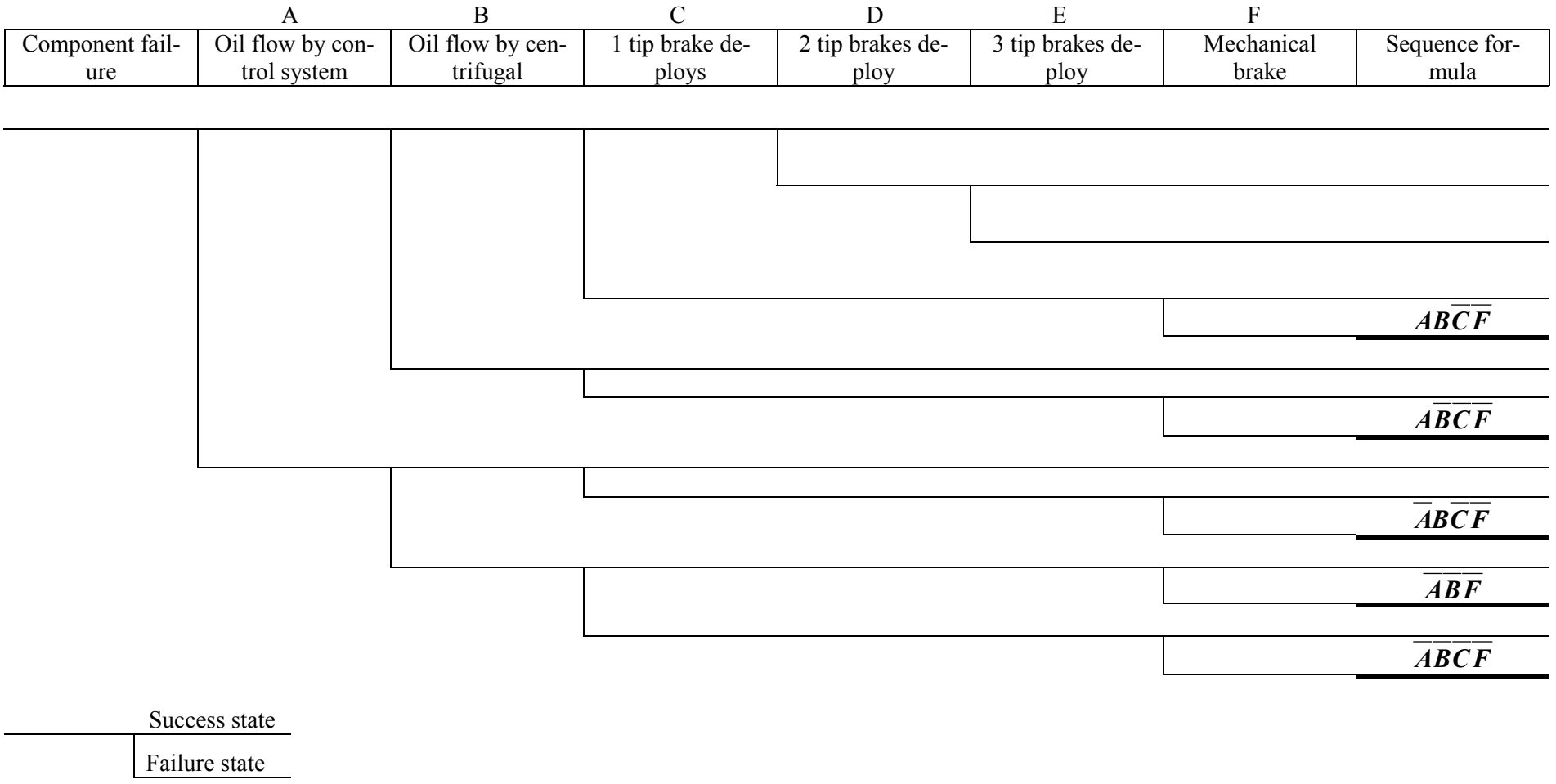


Figure 2. Event tree for initiating event "Grid loss" and condition "10 m/s≤ws<20 m/s"

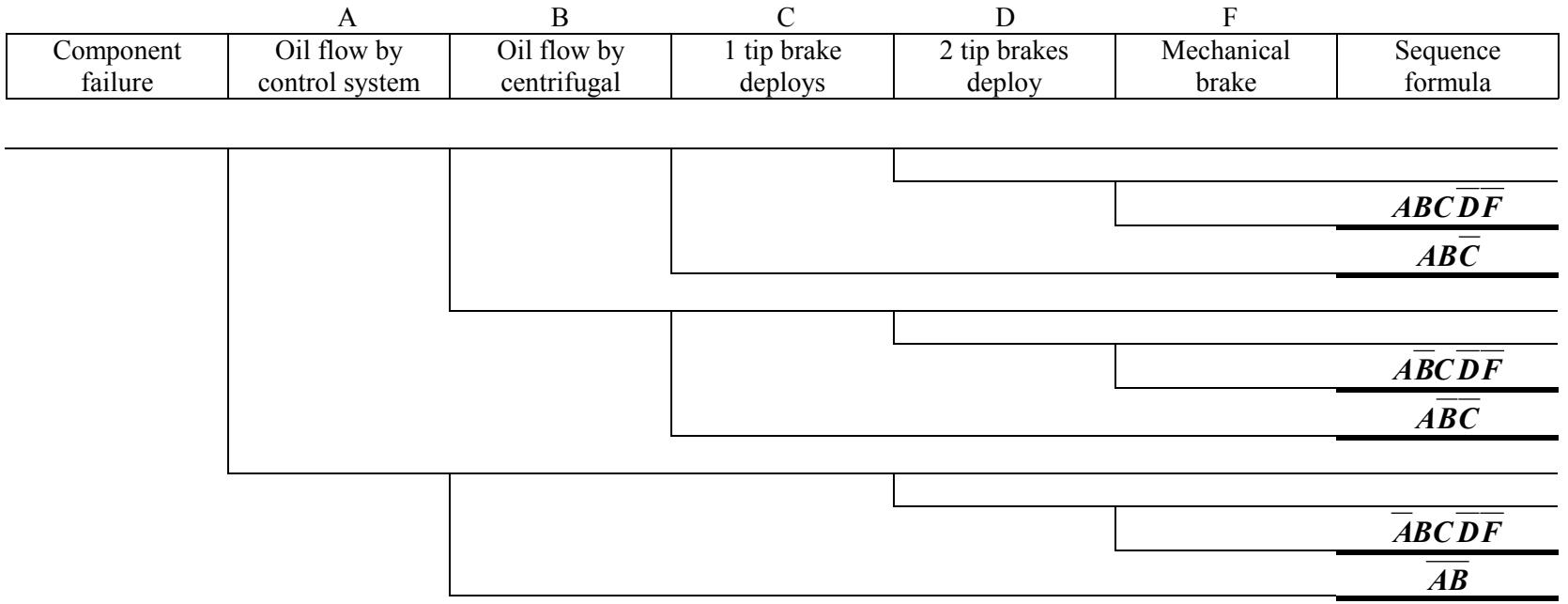


Figure 3. Event tree for initiating event "Grid loss" and condition "20 m/s≤ws<25 m/s"

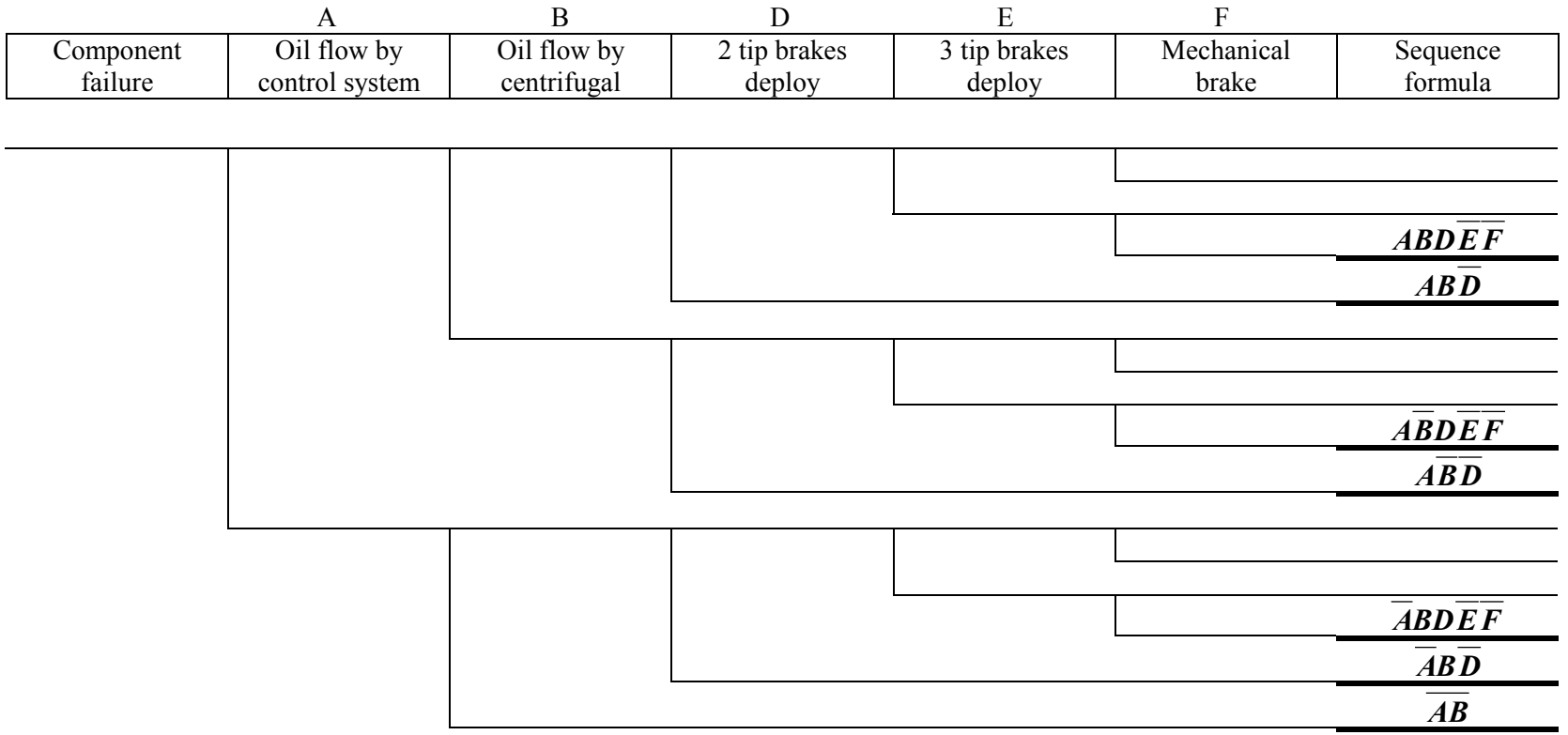


Figure 4. Event tree for initiating event "Gearbox failure" and condition "5 m/s≤ws<10 m/s"

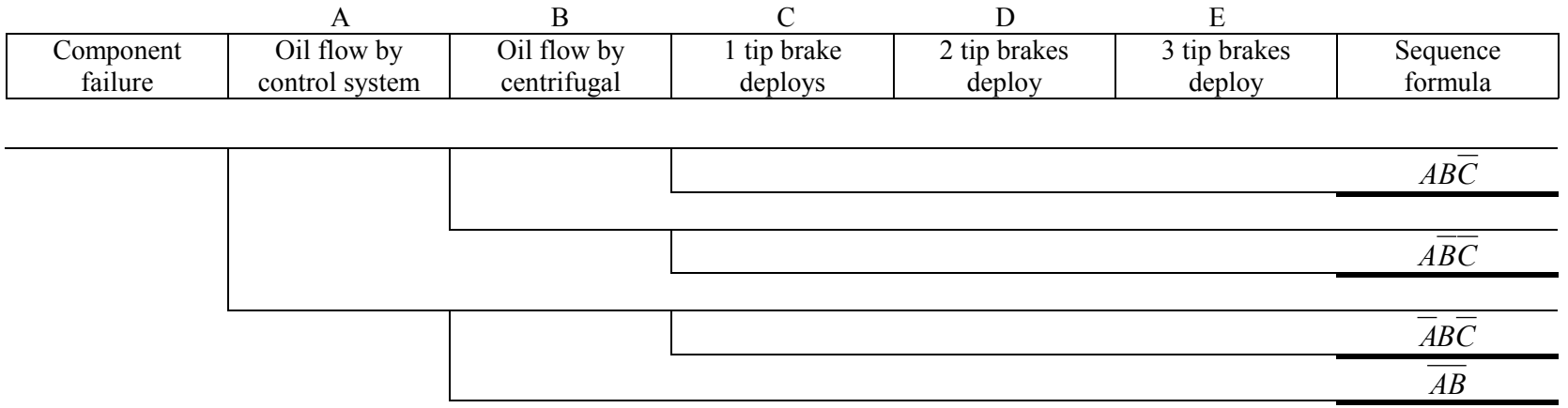


Figure 5. Event tree for initiating event "Gearbox failure" and condition "10 m/s≤ws<20 m/s"

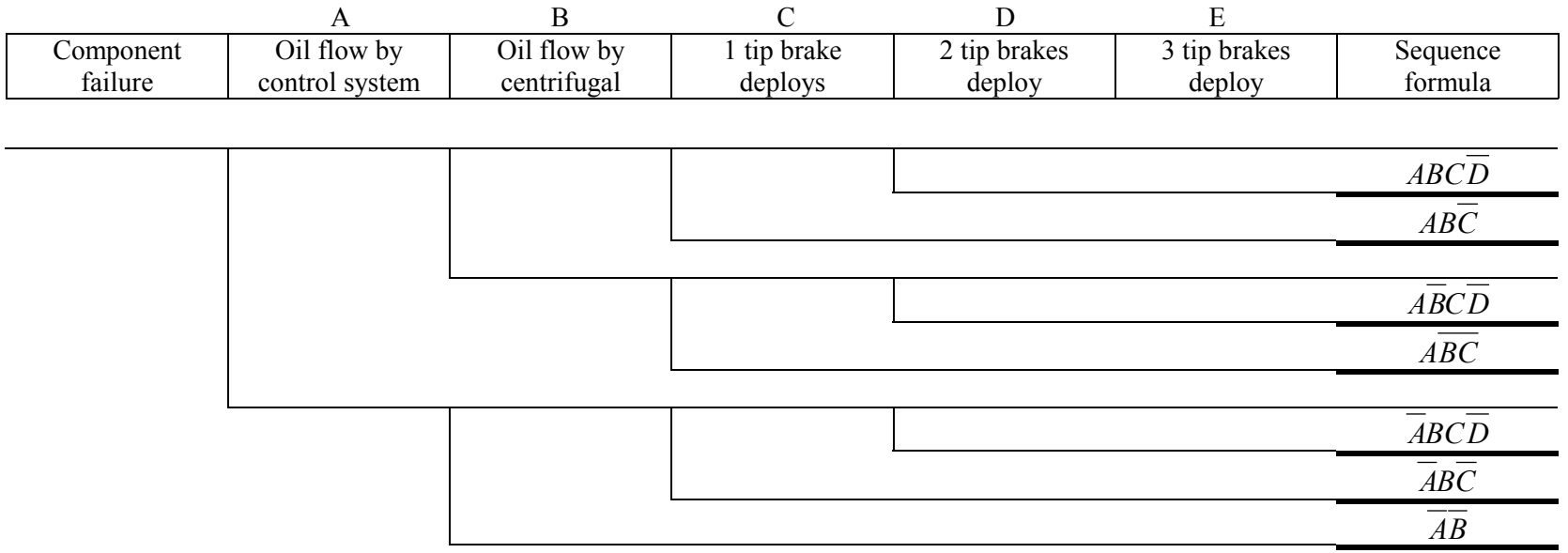


Figure 6. Event tree for initiating event "Gearbox failure" and condition "20 m/s≤ws<25 m/s"

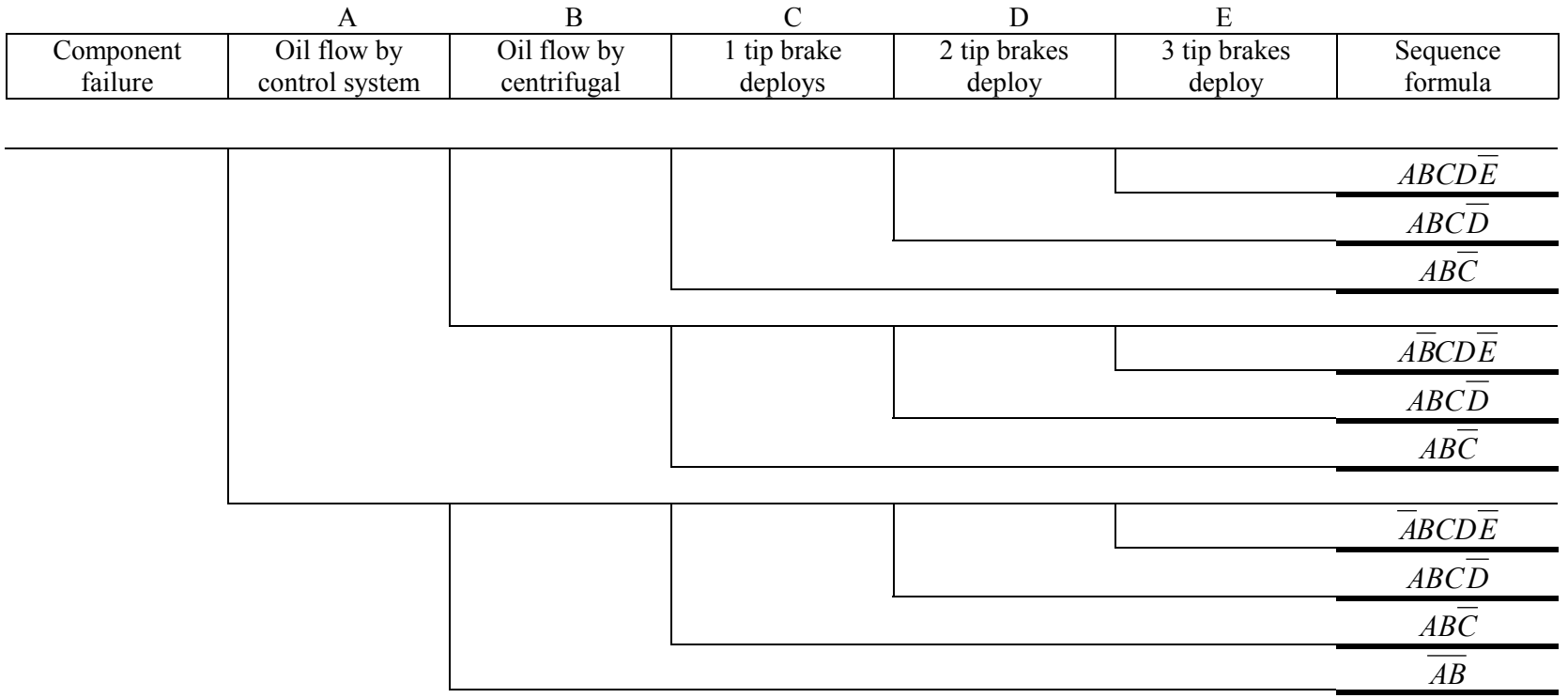
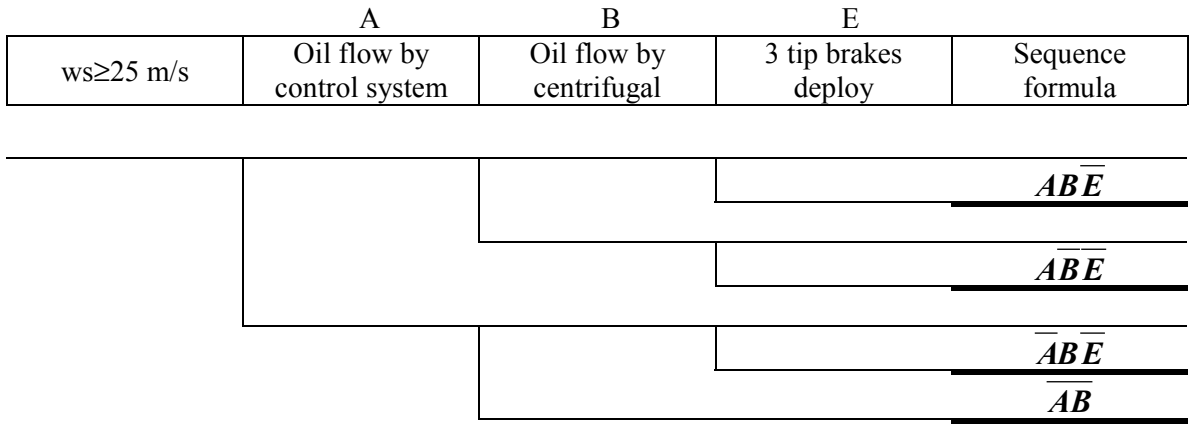
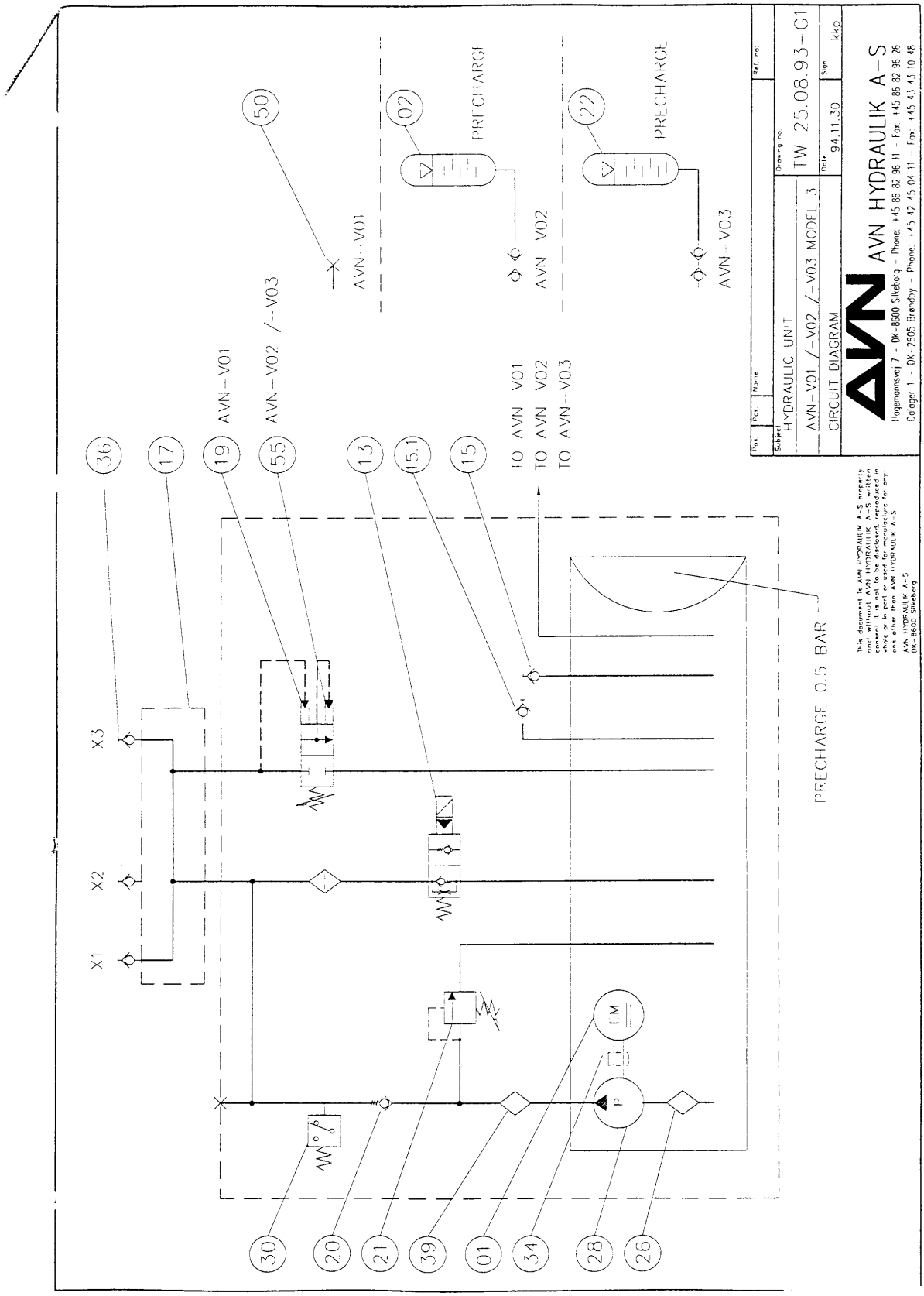


Figure 7. Event tree for initiating event "ws≥25 m/s"



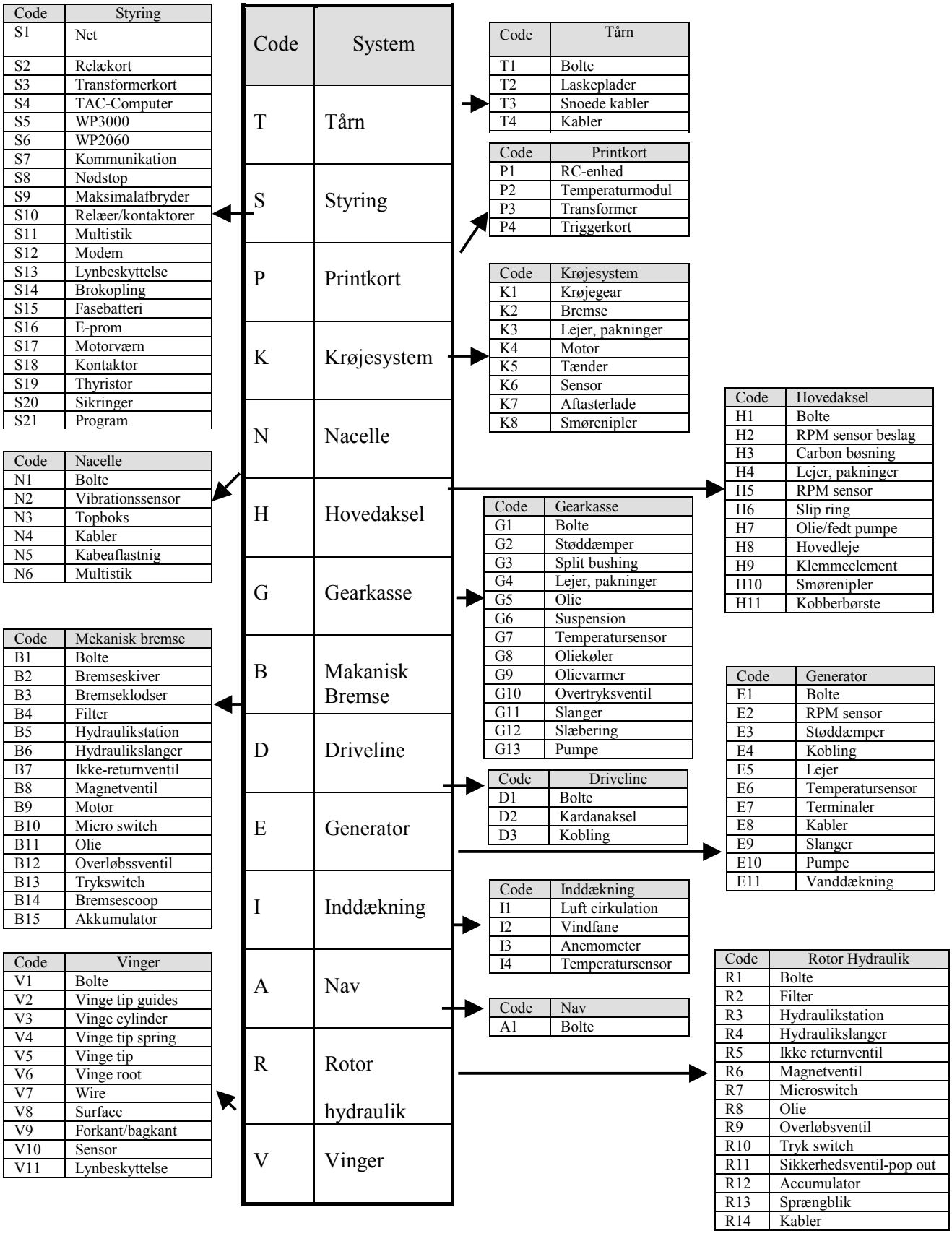
APPENDIX II

Diagram of the Hydraulic System


AVN HYDRAULIK A-S
Hagemannsvej 7 - DK-8600 Silkeborg - Phone: +45 86 82 96 11 - Fax: +45 86 82 96 26
Dalager 1 - DK-2605 Brøndby - Phone: +45 43 45 04 11 - Fax: +45 43 43 10 48
HYDRAULIC UNIT
AVN-V01 /-V02 /-V03 MODEL 3
CIRCUIT DIAGRAM
Drawing no. TW 25.08.93-G1
Date 94.11.30
Sign. kkp
PRECHARGE 0.5 BAR
TO AVN-V01
TO AVN-V02
TO AVN-V03
AVN-V01
AVN-V02 /-V03
AVN-V01
AVN-V02
AVN-V03
PRECHARGE
PRECHARGE
X1
X2
X3
FM
P

Appendix III

Subsidiary Tables Providing the System and Component Codes



Code	System
T	Tårn
S	Styring
P	Printkort
K	Krøjesystem
N	Nacelle
H	Hovedaksel
G	Gearkasse
B	Makanisk Bremse
D	Driveline
E	Generator
I	Inddækning
A	Nav
R	Rotor hydraulik
V	Vinger

Code	Styring
S1	Net
S2	Relækort
S3	Transformerkort
S4	TAC-Computer
S5	WP3000
S6	WP2060
S7	Kommunikation
S8	Nødstop
S9	Maksimalafbryder
S10	Relæer/kontaktorer
S11	Multistik
S12	Modem
S13	Lynbeskyttelse
S14	Brokopling
S15	Fasebatteri
S16	E-prom
S17	Motorværn
S18	Kontaktor
S19	Thyristor
S20	Sikringer
S21	Program

Code	Nacelle
N1	Bolte
N2	Vibrationssensor
N3	Topboks
N4	Kabler
N5	Kabeaflastnig
N6	Multistik

Code	Mekanisk bremse
B1	Bolte
B2	Bremseskiver
B3	Bremseklodser
B4	Filter
B5	Hydraulikstation
B6	Hydraulikslanger
B7	Ikke-returnventil
B8	Magnetventil
B9	Motor
B10	Micro switch
B11	Olie
B12	Overløbssventil
B13	Trykswitch
B14	Bremsescoop
B15	Akkumulator

Code	Vinger
V1	Bolte
V2	Vinge tip guides
V3	Vinge cylinder
V4	Vinge tip spring
V5	Vinge tip
V6	Vinge root
V7	Wire
V8	Surface
V9	Forkant/bagkant
V10	Sensor
V11	Lynbeskyttelse

Code	Tårn
T1	Bolte
T2	Laskeplader
T3	Snoede kabler
T4	Kabler

Code	Printkort
P1	RC-enhed
P2	Temperaturmodul
P3	Transformer
P4	Triggerkort

Code	Krøjesystem
K1	Krøjegear
K2	Bremse
K3	Lejer, pakninger
K4	Motor
K5	Tænder
K6	Sensor
K7	Aftasterlade
K8	Smørenipler

Code	Hovedaksel
H1	Bolte
H2	RPM sensor beslag
H3	Carbon bøsning
H4	Lejer, pakninger
H5	RPM sensor
H6	Slip ring
H7	Olie/fedt pumpe
H8	Hovedleje
H9	Klemmeelement
H10	Smørenipler
H11	Kobberbørste

Code	Gearkasse
G1	Bolte
G2	Støddæmper
G3	Split bushing
G4	Lejer, pakninger
G5	Olie
G6	Suspension
G7	Temperatursensor
G8	Oliekøler
G9	Olievarmer
G10	Overtryksventil
G11	Slanger
G12	Slæbering
G13	Pumpe

Code	Driveline
D1	Bolte
D2	Kardanaksel
D3	Kobling

Code	Generator
E1	Bolte
E2	RPM sensor
E3	Støddæmper
E4	Kobling
E5	Lejer
E6	Temperatursensor
E7	Terminaler
E8	Kabler
E9	Slanger
E10	Pumpe
E11	Vanddækning

Code	Inddækning
I1	Luft cirkulation
I2	Vindfane
I3	Anemometer
I4	Temperatursensor

Code	Nav
A1	Bolte

Code	Rotor Hydraulik
R1	Bolte
R2	Filter
R3	Hydraulikstation
R4	Hydraulikslanger
R5	Ikke returnventil
R6	Magnetventil
R7	Microswitch
R8	Olie
R9	Overløbsventil
R10	Tryk switch
R11	Sikkerhedsventil-pop out
R12	Accumulator
R13	Sprængblik
R14	Kabler

Repair Action

Code	Name
1	Genanvendes
2	Genstartet via remote
3	Genstartet i Vindmøllen
4	Hejsning
5	Inspiceret
6	Installeret
7	Justeret
8	Påført
9	Påfyldt
10	Renset
11	Samling
12	Spændt
13	Udført
14	Udluftet
15	Udskiftet
16	Repareret

Detection Method

	Name
1	Planned maintenance
2	Operator
3	Overspeed
4	Vibration
5	Inverter temperature
6	Inverter control
7	Grid failures

Responsibility

Code	Name
1	Konstruktion og udvikling
2	Indkøb
3	Montage
4	Produktion
5	Garanti-service
6	Service

Failure Causes

Code	Name
A	Brandt
B	Defekt
C	Defekt/Lynnedslag
D	Kontrolleret
E	For stor
F	Irret
G	Knækket
H	Justeret
I	Løs
J	Løbskørsel
K	Monteret
L	Rengjort
M	Pitchet
N	Renoveret
O	Revnet
P	Rusten
Q	Sidder fast
R	Slidt
S	Støjer
T	Ude af justering
U	Udført
V	Udtaget
X	Udskiftet
Y	Udluftet
Z	Utæt

Appendix IV

Creating a new Microsoft Access workgroup information file

When you install Microsoft Access, the Setup program automatically creates a Microsoft Access workgroup information file that is identified by the name and organization information you specify. Because this information is often easy to determine, it is possible for unauthorized users to create another version of this workgroup information file and consequently irrevocably assume the permitted operations of an administrator account (i.e. an Admins group user) in the workgroup defined by that workgroup information file. To prevent this, you should therefore create a new workgroup information file and specify a workgroup ID (WID). Thereafter only persons knowing the new WID will be able to create a copy of the workgroup information file.

1. Exit Microsoft Access.
2. To start the "Workgroup Administrator", do one of the following, depending on which operating system you are using:

- If you are using Windows 95, use "My Computer" or "Windows Explorer" to open the "System" subfolder in the Windows folder, and then double-click "Wrkgadm.exe".
- If you are using Windows NT Workstation 4.0, use "My Computer" or "Windows Explorer" to open the "System32" subfolder in the WinNT folder, and then double-click "Wrkgadm.exe".
- If you are using Windows NT Workstation 3.51, open "Program Manager", and then double-click the "Workgroup Administrator" icon in the program group where you installed Microsoft Access.

3. In the "Workgroup Administrator" dialogue box, click "Create", and then type your name and organization.
4. In the "Workgroup Owner Information" dialogue box, type any combination of up to 20 numbers and letters, and then click "OK".

Caution: Be sure to write down your exact name, organization, and workgroup ID, carefully distinguishing between upper-case and lower-case letters for all three entries and store the information in a safe place. If you have to re-create the workgroup information file, you must supply exactly the same name, organization, and workgroup ID. If you forget or lose these entries, you cannot recover them and might lose access to your databases.

5. Type a new name for the new workgroup information file, and then click "OK". (By default, the workgroup information file is saved in the folder where you installed Microsoft Access. To save in a different location, type a new path or click "Browse" to specify the new path).

The new workgroup information file is used the next time you start Microsoft Access. Any user and group accounts or passwords you create are saved in the new workgroup information file. To have others join the workgroup defined by your new workgroup information file, copy it to a shared folder (if you did not already save it in a shared folder in step 4), and then have each user run the "Workgroup Administrator" to join the new workgroup information file.

Appendix V

Glossary of WTB construction and maintenance terms

Aftasteplade	
Akkumulator	Accumulator
Anemometer	Anemometer
Bolte	Bolts
Bremse	Brake
Bremseklodser	Brake shoes
Bremsescoop	Brake scoop
Bremseskive	Brake disc
Brokobling	Bridge coupling
Brændt	Burnt
Carbon bøsning	Carbon bushing
Kardanaksel	Cardan shaft
Defekt	Defective
Defekt/Lynnedslag	Defective/Struck by lightning
Fasebatteri	Phase battery
Filter	Filter
For stor	Too large
Forkant/bagkant	Front edge/back edge
Garanti-service	Warranty service
Gearkasse	Gear box
Genanvendes	To be reused
Genstartet i vindmøllen	Restarted in the wind turbine
Genstartet via remote	Restart via remote
Hejsning	Hoist
Hovedaksel	Main shaft
Hovedleje	Main bearing
Hydraulikslanger	Hydraulic hoses
Hydraulikstation	Hydraulic station
Ikke-returventil	Non return valve
Inddækning	Cover
Indkøb	Purchase dept.
Inspiceret	Inspected
Installeret	Installed
Irret	Corroded
Justeret	Adjusted
Kabelaflastning	Cable relief
Kabler	Cables
Klemmeelement	Clamp
Knækket	Broken
Kobberbørste	Copper brush
Kobling	Coupling
Kommunikation	Communication
Konstruktion og udvikling	Construction and development
Kontaktor	Power relay
Kontrolleret	Controlled
Krøjegear	Yawing gear
Krøjesystem	Yawing system

Laskeplader	Fish plate
Lejer	Bearings
Lejer, pakninger	Bearing seal
Luftcirkulation	Air circulation
Lynbeskyttelse	Lightning protection
Løbskkørsel	Over-speed
Løs	Loose
Magnetventil	Magnet valve
Maksimalafbryder	Maximum circuit breaker
Montage	Mounting
Monteret	Mounted
Motorværn	Protective motor relay
Multistik	Multipin connector
Nacelle	
Nav	
Net	Mains
Nødstop	Emergency stop
Olie	Oil
Olie/fedt pumpe	Oil/grease pump
Oliekøler	Oil cooler
Olievarmer	Oil heater
Overløbsventil	Overflow valve
Overtryksventil	Pressure valve
Pitchet	Pitched
Produktion	Production
Pumpe	Pump
Påfyldt	Filled
Påført	Placed
RC-enhed	RC unit
Relæer/kontaktorer	Relays/Power relays
Relækort	Relay card
Rengjort	Cleaned
Renoveret	Renovated
Renset	Cleaned
Repareret	Repaired
Revnet	Fracture
Rotor Hydraulik	Rotor hydraulics
RPM sensor beslag	RPM sensor mounting
Rusten	Corroded
Samling	Connection
Sidder fast	Stuck
Sikkerhedsventil-pop out	Safety valve, pop-out
Sikringer	Fuses
Slanger	Hoses
Slidt	Worn out
Slip ring	Slip ring
Slæbering	Slip ring
Smørenipler	Grease nipples
Snoede kabler	Twisted cables
Sprængblik	
Spændt	Tensioned
Støddæmper	Shock absorber
Støjer	Noisy

TAC-computer	TAC computer
Temperaturmodul	Temperature module
Temperatursensor	Temperature sensor
Terminaler	Terminals
Topboks	Top box
Transformerkort	Transformer card
Triggerkort	Trigger card
Trykswitch	Pressure switch
Tænder	Teeth
Ude af justering	Out of adjustment
Udført	Carried out
Udluftet	Ventilated
Udskiftet	Exchanged
Udtaget	Removed
Utæt	Leaky
Vanddækning	Water cover
Vibrationssensor	Vibration sensor
Vindfane	Wind vane
Vinge cylinder	Wing cylinder
Vinge root	Wing root
Vinge tip	Wing tip
Vinge tip guides	Wing tip guides
Vinge tip spring	Wing tip spring
Wire	Wire
WP2060	WP2060
WP3000	WP3000

Bibliographic Data Sheet **Risø-R-1200(EN)**

Title and authors

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Igor Kozine, Palle Christensen and Martin Winther-Jensen

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	1210066

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47	6	11	3

Abstract (max. 2000 characters)

The objective of this project was to develop and establish a database for collecting reliability and reliability-related data, for assessing the reliability of wind turbine components and subsystems and wind turbines as a whole, as well as for assessing wind turbine availability while ranking the contributions at both the component and system levels. The project resulted in a software package combining a failure database with programs for predicting WTB availability and the reliability of all the components and systems, especially the safety system. The report consists of a description of the theoretical foundation of the reliability and availability analyses and of sections devoted to the development of the WTB reliability models as well as a description of the features of the database and software developed. The project comprises analysis of WTBs NM 600/44, 600/48, 750/44 and 750/48, all of which have similar safety systems. The database was established with Microsoft Access Database Management System, the software for reliability and availability assessments was created with Visual Basic.

Available on request from Information Service Department, Risø National Laboratory,
(Afdelingen for Informationsservice, Forskningscenter Risø), P.O.Box 49, DK-4000 Roskilde, Denmark.
Telephone +45 4677 4004, Telefax +45 4677 4013

Figure 1. Event tree for initiating event "Grid loss" and condition "5 m/s≤ws<10 m/s"

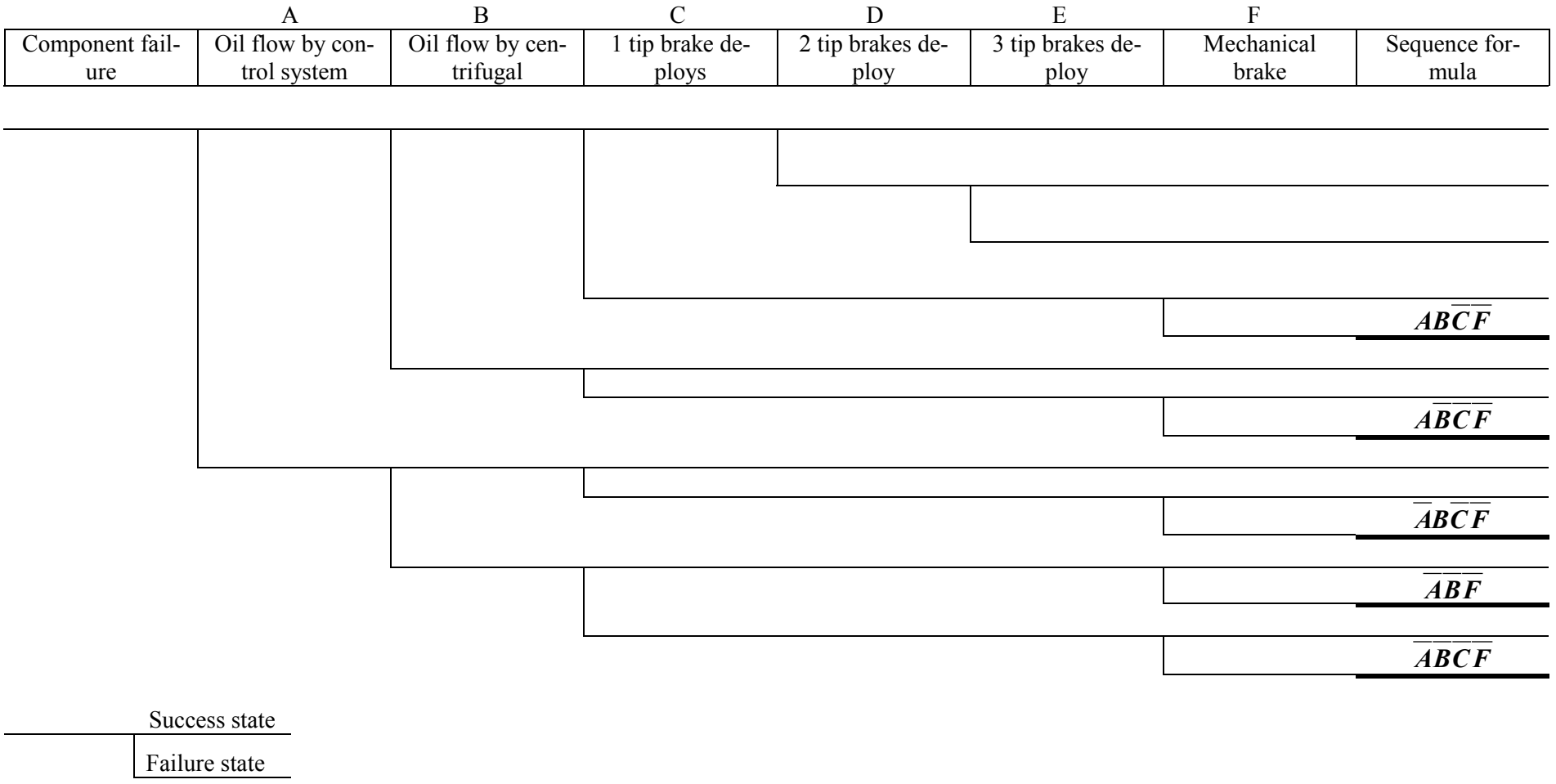

Figure 2. Event tree for initiating event "Grid loss" and condition "10 m/s≤ws<20 m/s"

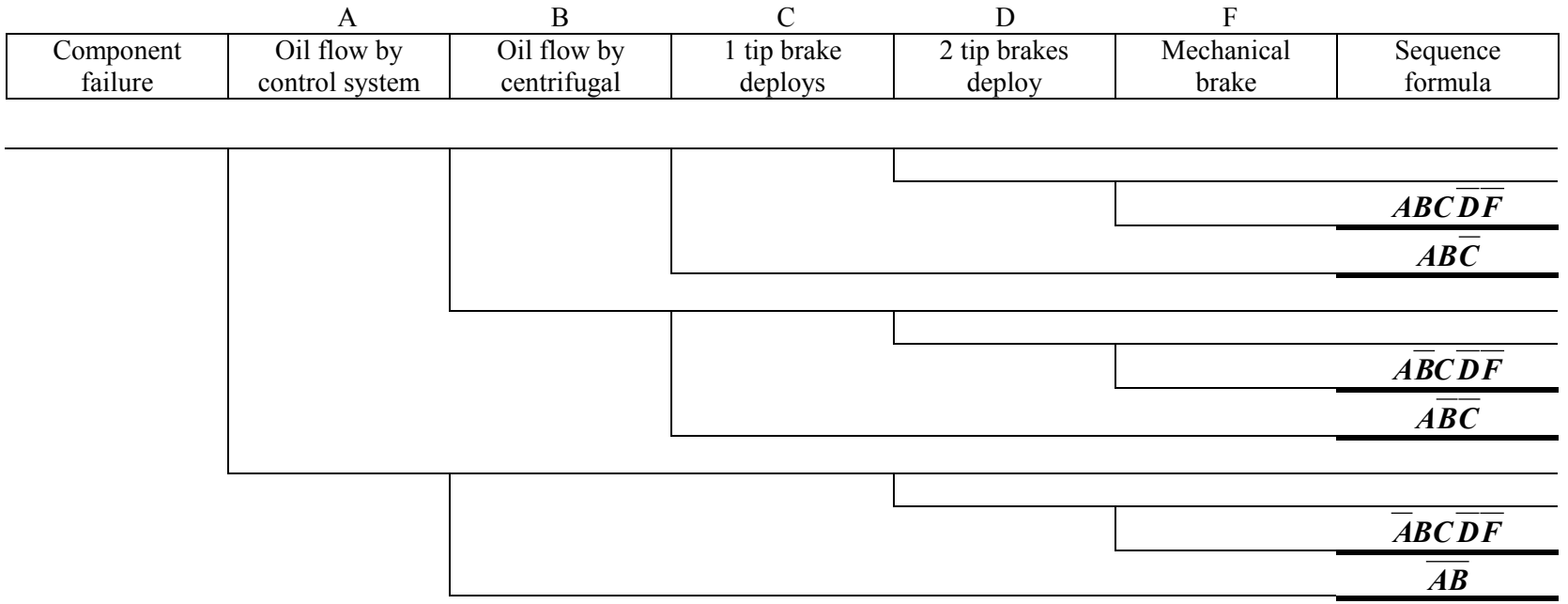

Figure 3. Event tree for initiating event "Grid loss" and condition "20 m/s≤ws<25 m/s"

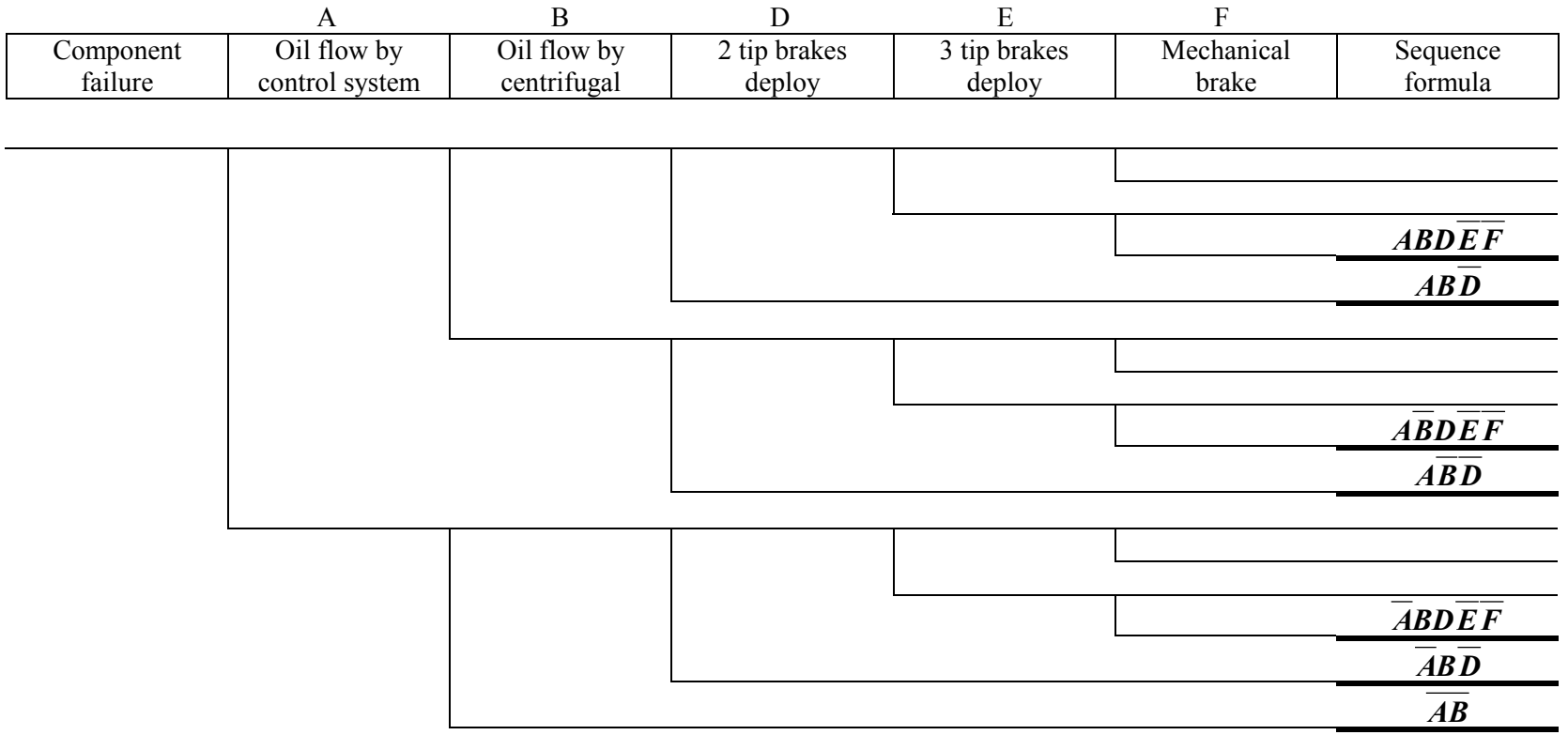

Figure 4. Event tree for initiating event "Gearbox failure" and condition "5 m/s≤ws<10 m/s"

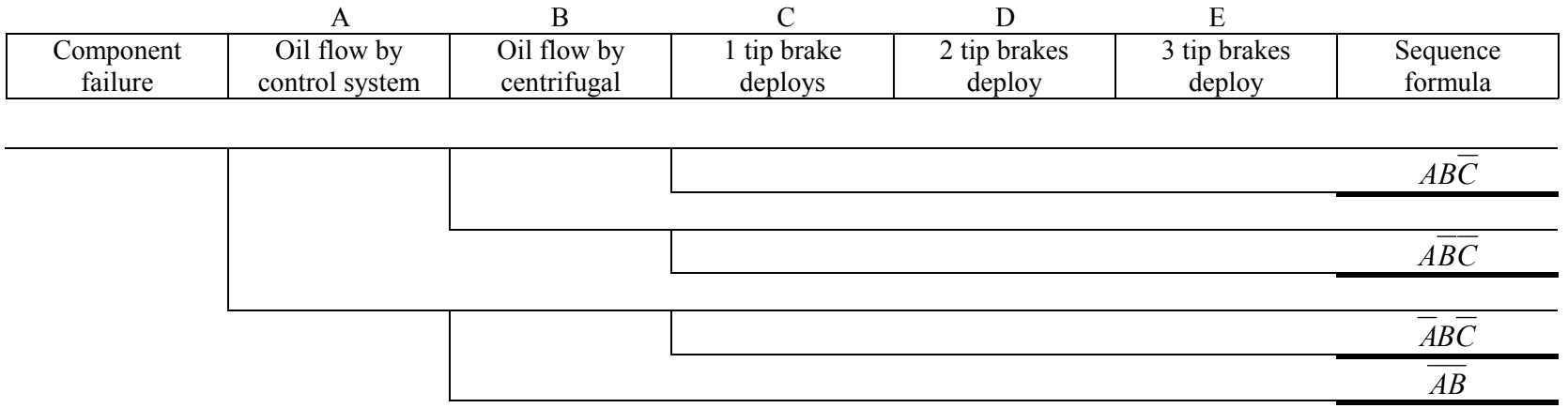

Figure 5. Event tree for initiating event "Gearbox failure" and condition "10 m/s≤ws<20 m/s"

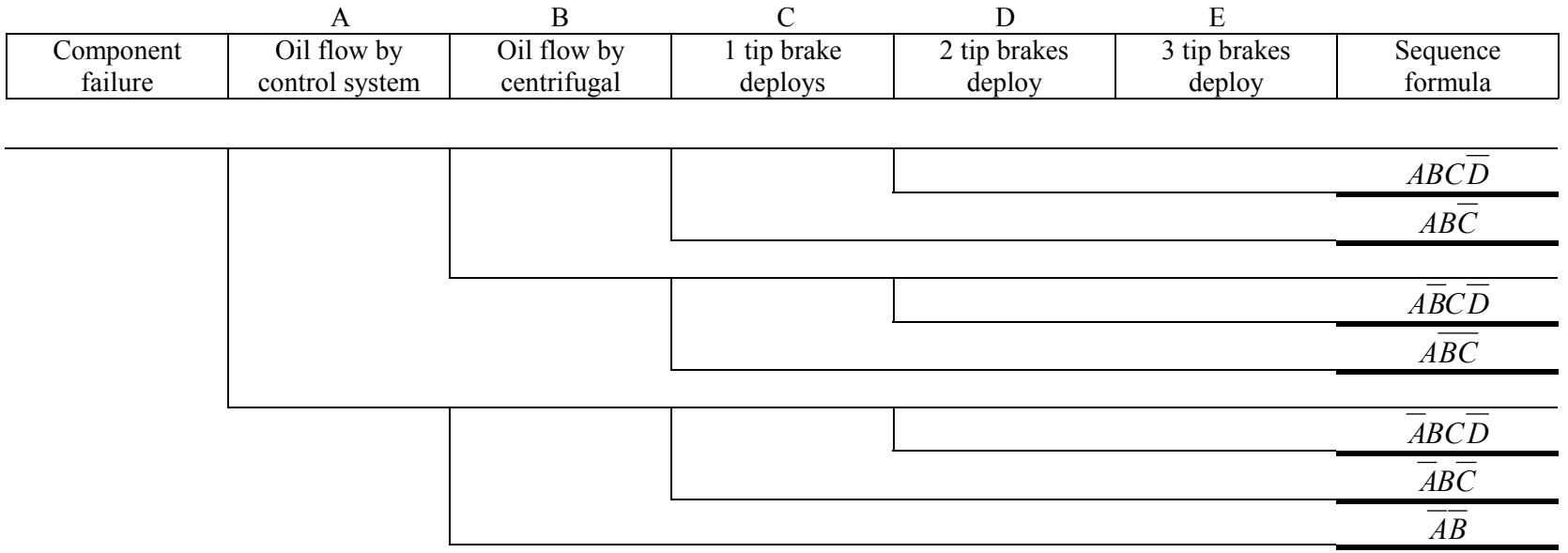

Figure 6. Event tree for initiating event "Gearbox failure" and condition "20 m/s≤ws<25 m/s"

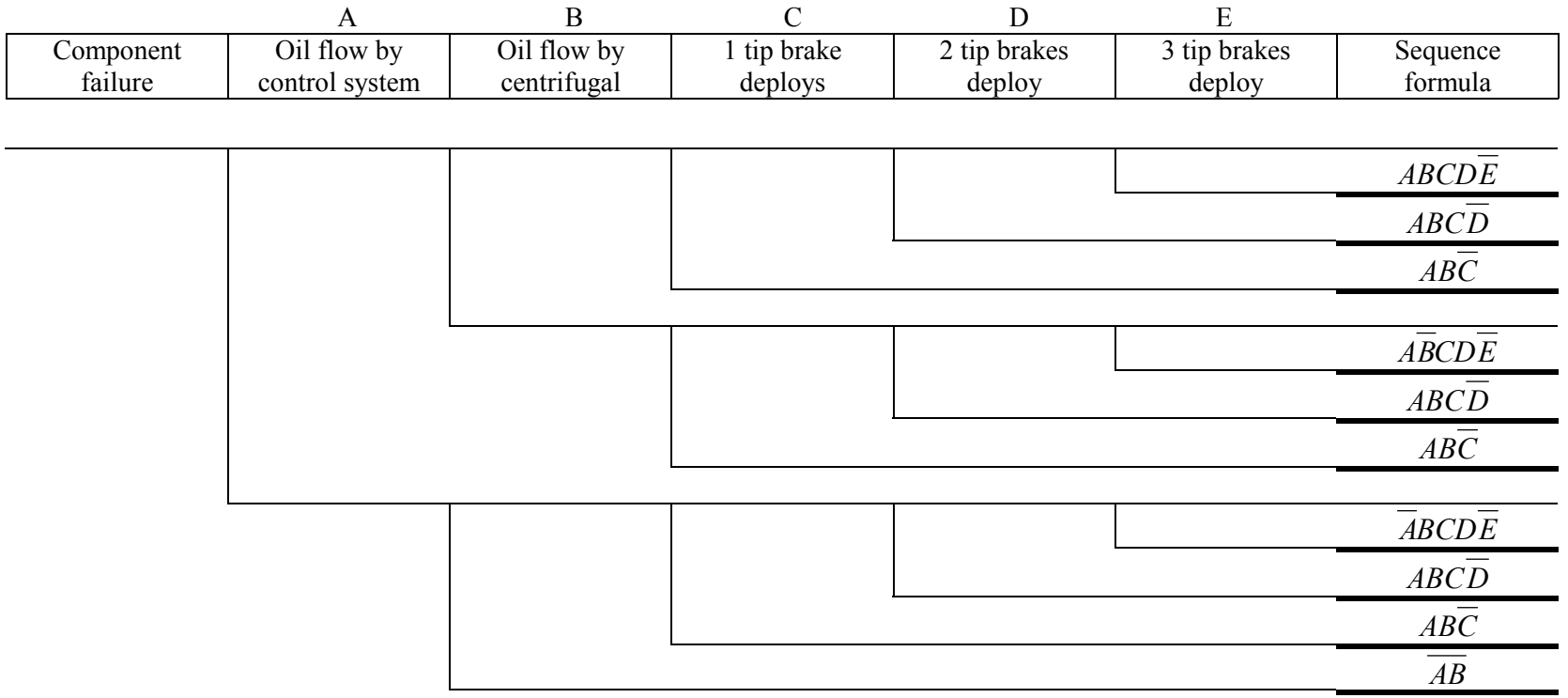

Figure 7. Event tree for initiating event "ws≥25 m/s"